

5 MODELS VERSUS OBSERVATIONS IN THE RECENT PAST

Chapter summary

Climate models show warming biases in many aspects of their reproduction of the past several decades. In response to estimated changes in forcing they produce too much warming at the surface (except in the models with lowest ECS), too much warming in the lower-and mid-troposphere and too much amplification of warming aloft.

Climate models also produce too much recent stratospheric cooling, invalid hemispheric albedos, too much snow loss, and too much warming in the Corn Belt. The IPCC has acknowledged some of these issues but not all.

5.1 Introduction

Climate models are the primary tool used to project future climate changes in response to increasing atmospheric levels of anthropogenic greenhouse gases. To assess the fitness of climate models for this purpose, it is reasonable to ask how well they reproduce the current climate and its variations over the past century. The box “Climate modeling” gives some detail on how climate models work.

Of great concern is the fact that, after several decades of the climate modeling enterprise involving approximately three dozen models operated by research centers around the world, the range of future warming they produce in response to a hypothetical doubling of atmospheric CO₂ extends over a factor of three, as we discussed in the previous chapter. This range of disagreement among models has not decreased for decades.

Problems with climate models are not just in their disagreement over the future, but also in their ability to replicate the recent past. Here we review some of the most important metrics of climate model accuracy: ability to reproduce historical surface, tropospheric and stratospheric temperature trends; ability to reproduce the vertical warming profile; and ability to reproduce other climate features such as snowfall. In all cases a persistent finding is that models on average err on the side of too much warming in response to estimated historical forcings.

BOX: Climate modeling

Most climate models, except for the simplest ones, represent Earth's land surface using a grid of squares on the order of 100 km wide. To simulate the atmosphere, typically 30 or more grid boxes are stacked above these squares. The ocean is modeled using a similar but finer grid, resulting in tens of millions of grid boxes for the atmosphere and oceans.

The computer models, based on physical laws, calculate how air, water, and energy move between grid boxes over time. The time step can be as small as 10 minutes, and repeating this process millions of times allows the simulation of climate over centuries. Running these models, even on the most powerful supercomputers, can take months. Comparing simulation results with historical climate data helps assess the accuracy of a model, while projections into the future estimate climate changes under assumed human and natural influences.

Despite sounding straightforward, climate modeling is highly complex. Many critical processes occur at scales smaller than the grid size. For instance, the flows of sunlight and heat in the atmosphere depend strongly on cloud cover. Since tracking individual clouds is impractical, researchers must make “subgrid” assumptions about the distribution of clouds in each grid box. Snow and ice cover, which affects how much sunlight is reflected or absorbed by the surface, is another subgrid factor.

Each subgrid assumption requires numerical parameters, which must be carefully set. Modelers initially estimate these parameters based on physics and observed climate patterns, then run the model. Because early results often diverge significantly from real-world observations, they “tune” these parameters to better match observed climate features. Different modeling teams use distinct assumptions and tuning strategies, leading to varied outcomes. Tuning is a necessary but delicate aspect of climate modeling, as it is for any complex system. Poor tuning can result in inaccurate simulations, while excessive tuning risks artificially steering results toward predetermined conclusions.

The spread of model representations of the current climate is very wide. One of the most basic indicators—Earth's average surface temperature—varies by about 3°C across CMIP6 models prior to 1880 (Figure 5.1), narrows slightly until 2040 then diverges to over 4 °C. For comparison 20th century warming was only about 1.0°C. This variation suggests substantial differences among models' physical processes.

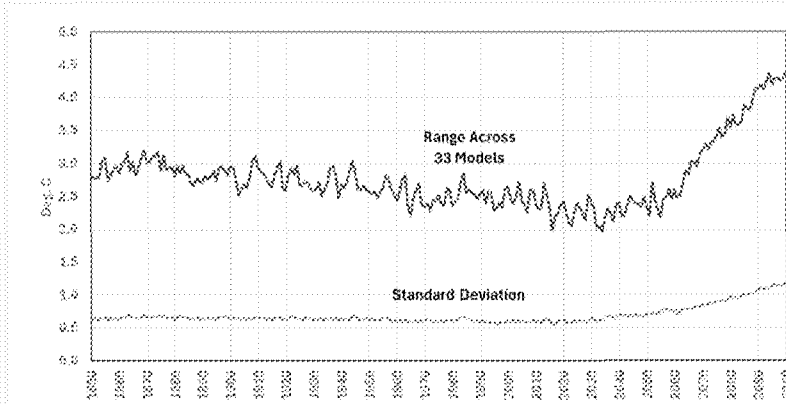


Figure 5.1 CMIP6 Average surface temperature range across 33 models and standard deviation using SSP5-85 scenario. Data from KNMI Climate Explorer website at <https://climexp.knmi.nl/start.cgi>.

Beyond the models' ability to reproduce features of today's climate, the critical issue for society is how well they predict responses to subtle human influences, such as greenhouse gas emissions, aerosol cooling, and land-use changes. The most crucial aspect that models must capture correctly is “feedbacks.” These occur when climate changes either amplify or suppress further warming. In general, the modeled net effect of all feedbacks doubles or triples the direct warming impact of CO₂.

5.2 Surface warming

A straightforward test of a climate model’s validity is its ability to reproduce historical warming in response to known past changes in climate drivers such as greenhouse gases. Figure 5.2 is reproduced from Scafetta (2023), that groups the latest-generation (CMIP6) climate models into low ECS (1.5 to 3.0 degrees C), medium ECS (3.0 to 4.5 degrees C) and high ECS (4.5 to 6.0 degrees C), and compares their post-1980 global average temperature simulation ranges to those of three surface temperature records and one satellite-based lower troposphere temperature data product.

The leftmost column shows that the low-ECS models track the post-1980 historical warming record reasonably well, but the middle and right columns show that the medium- and high-ECS models conspicuously over-predict the warming.

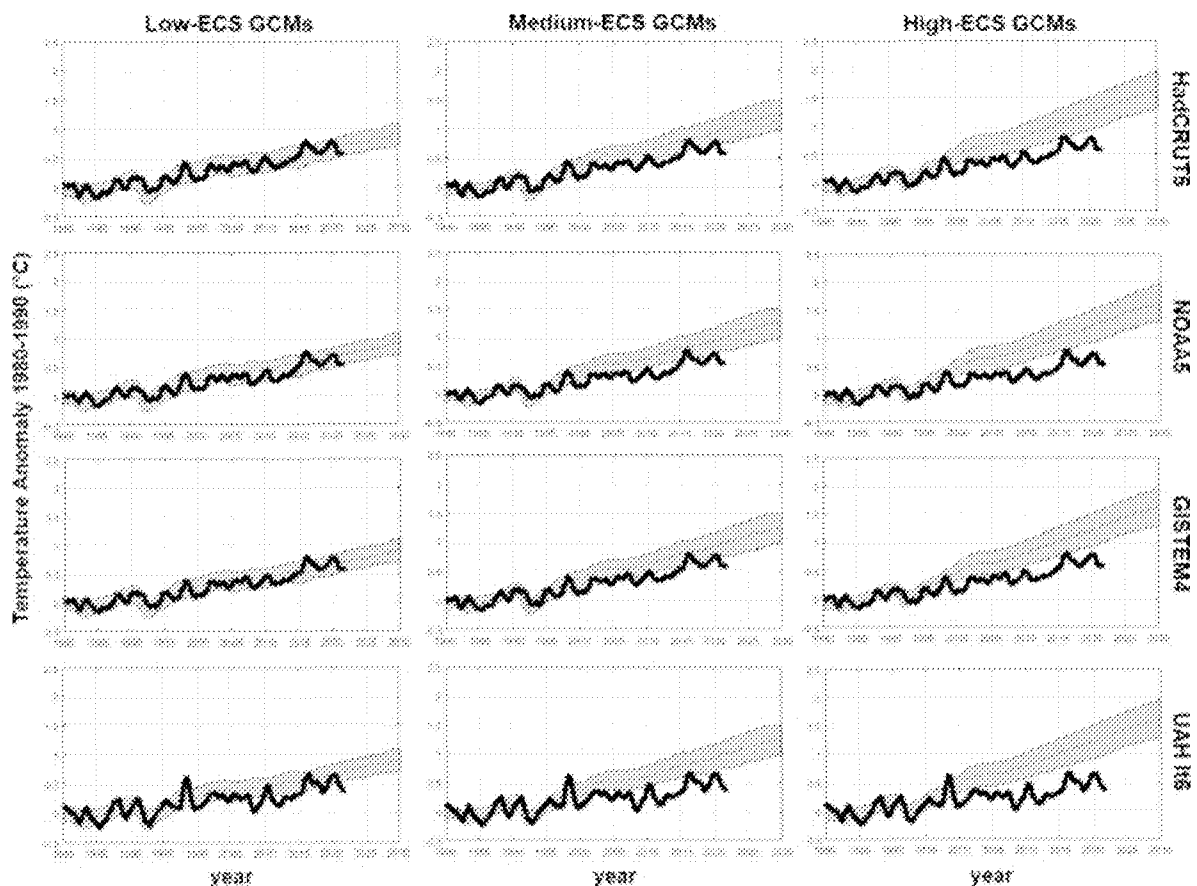


Figure 5.2: Model-Observational comparisons for Earth’s surface warming. The columns correspond to model groups showing low-ECS to high-ECS, while the rows correspond to widely-used observed temperature records, the first three showing surface averages and the fourth showing the lower troposphere average. In each panel the yellow area denotes the mean and range ($\pm$ one standard deviation) of climate model simulations for that group. The thick black line shows the observed annual average temperature in the indicated source. Source: Scafetta (2023) Fig.2.

Spencer (2024) has also provided a useful summary of the Model-Observation mismatch by comparing trends in surface temperature data products with those in individual climate models, as summarized in Figure 5.3; most climate models show substantially more warming than the observations since 1979.

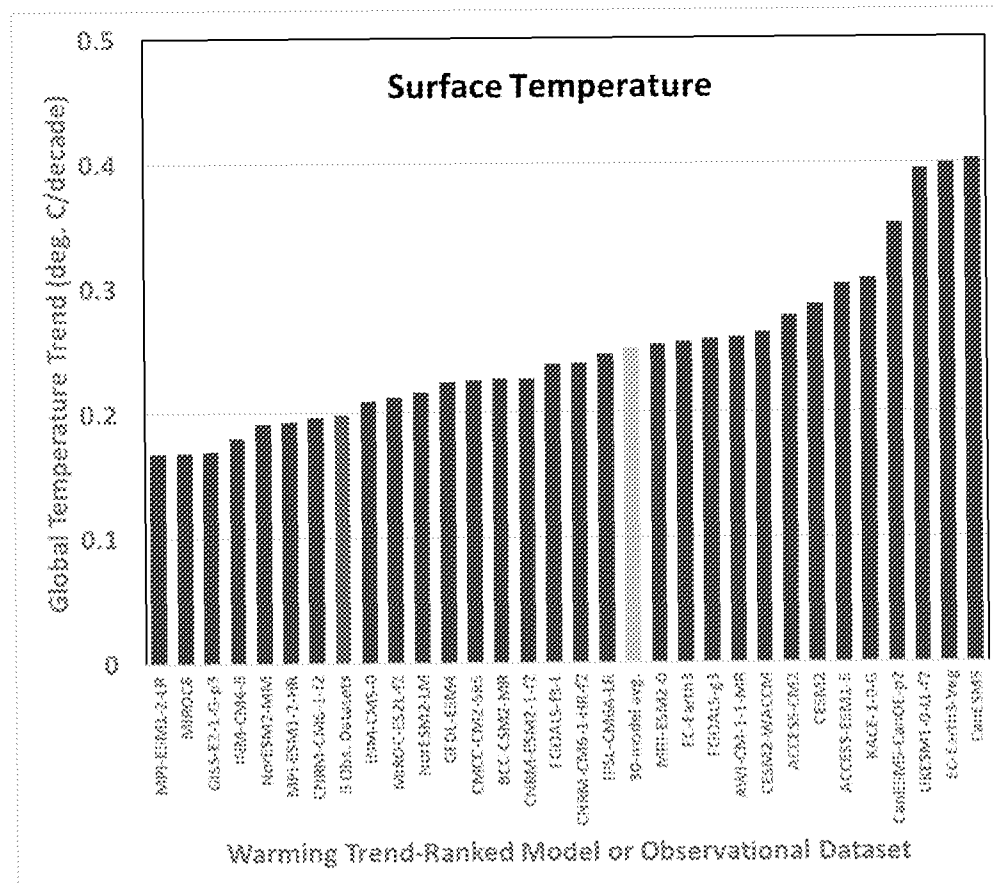


Figure 5.3 Global surface air temperature trends (°C/decade), 1979-2024, from various CMIP6 climate models (red, 30-model average in orange); and the average of three thermometer datasets (HadCRUT5, NOAA Global Temp, and Berkeley 1 deg.) and two reanalysis datasets (ERA5 and NCEP/NCAR R1) in blue. Data source: <https://climexp.knmi.nl/start.cgi>.

5.3 Tropospheric warming

It has long been known that climate models on average overstate warming in the tropical troposphere. This region is an important test of climate models since this is where the signal of anthropogenic greenhouse warming emerges first and most strongly. Biases in tropospheric trends indicate model flaws in heat transfer processes that carry over to surface warming biases.

The discrepancy was flagged as a serious inconsistency in the first U.S. Climate Change Science Program report (Karl *et al.* 2006) and has been mentioned in every IPCC report since, but the discrepancy has gotten worse over time, and the bias is now global. McKittrick and Christy (2020) compared tropospheric warming trends in CMIP6 climate models to observed trends from satellites, weather balloons and reanalysis systems. Every model overpredicted the average observed warming trend over 1979-2014 in both Lower- and Mid-Troposphere layers, both globally and in the tropics. In most individual models the bias was statistically significant and on average across models it was highly significant.

Figure 5.4 presents the comparisons with data updated to 2024 (McKittrick and Christy 2025). The recent warm years moved the observed trend up slightly and widened the trend confidence intervals but the overall pattern remains the same: model bias is towards too much warming, in most cases the difference is statistically significant and on average the bias is statistically highly significant. McKittrick and Christy (2020) also showed that the bias is larger in high-ECS models, but even the models with lower average ECS predict too much warming. If future climate models were to realistically represent global tropospheric warming, they would likely be less sensitive than even the low-ECS members of the CMIP6 ensemble.

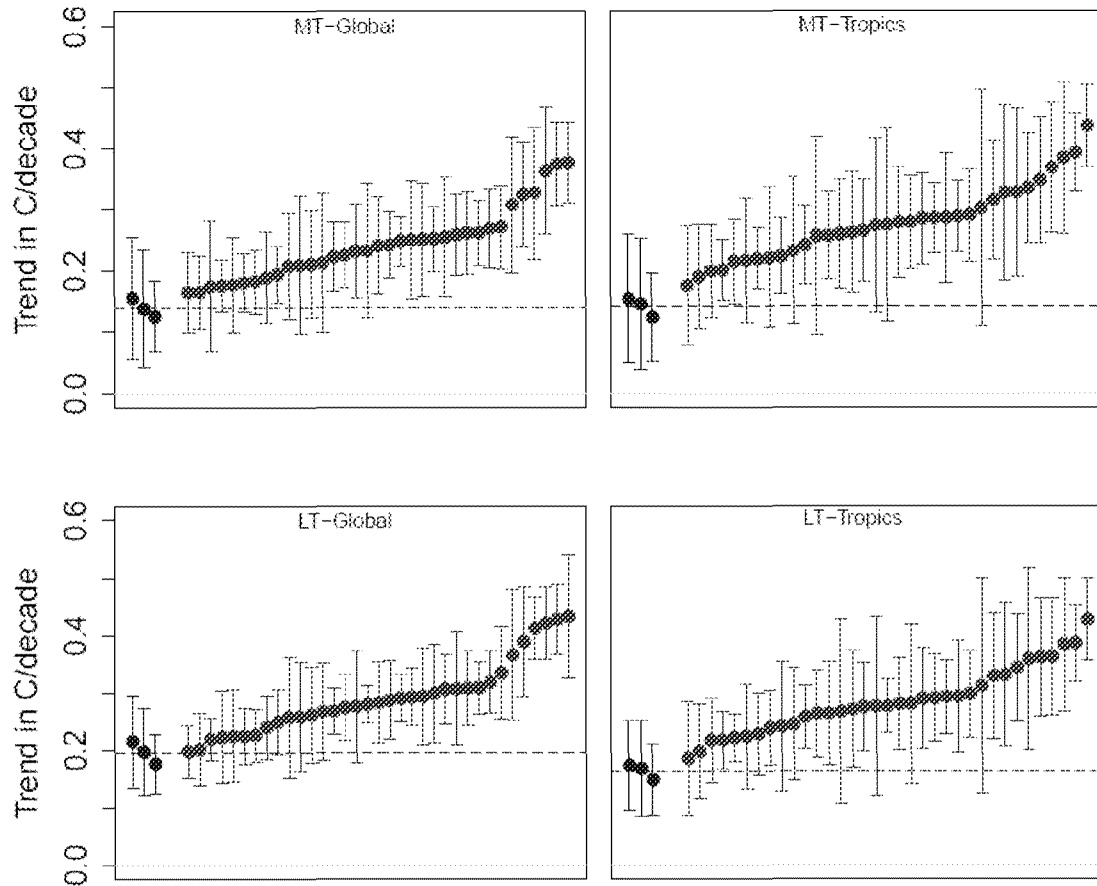


Figure 5.4: Observed versus CMIP6 modeled warming trends (°C/decade 1979-2024) in the global and tropical lower (LT) and mid-troposphere (MT). Uses methodology of McKittrick and Christy (2020) on data updated from 2014 to 2024. Blue dots: warming trends with 95 percent confidence intervals for 3 data products (radiosondes, reanalysis, and satellites). Blue dashed line: warming trend average for 3 observed series. Red dots: modeled warming trends with 95 percent confidence intervals in 35 models arranged lowest to highest.

As mentioned previously, the IPCC has long acknowledged the model-observation mismatch. For example, AR6 pp. 443-444 offers this on the tropical troposphere (it does not address the global comparison):

Several studies since AR5 have continued to demonstrate an inconsistency between simulated and observed temperature trends in the tropical troposphere, with models simulating more warming than observations (Mitchell *et al.*, 2013, 2020; Santer *et al.*, 2017a, b; McKittrick and Christy, 2018; Po-Chedley *et al.*, 2021)... Over the 1979–2014 period, models are more consistent with observations in the lower troposphere, and least consistent in the upper troposphere around 200 hPa, where biases exceed 0.1°C per decade. Several studies using CMIP6 models suggest that differences in climate sensitivity may be an important factor contributing to the discrepancy between the simulated and observed tropospheric temperature trends (McKittrick and Christy, 2020; Po-Chedley *et al.*, 2021), though it is difficult to deconvolve the influence of climate sensitivity, changes in aerosol forcing and internal variability in contributing to tropospheric warming biases (Po-Chedley *et al.*, 2021). Another study found that the absence of a hypothesized negative tropical cloud feedback could explain half of the upper troposphere warming bias in one model (Mauritsen and Stevens, 2015).

... In summary, studies continue to find that CMIP5 and CMIP6 model simulations warm more than observations in the tropical mid- and upper-troposphere over the 1979–2014 period (Mitchell *et al.*, 2013, 2020; Santer *et al.*, 2017a, b; Suárez-Gutiérrez *et al.*, 2017; McKittrick and Christy, 2018), and that overestimated surface warming is partially responsible (Mitchell *et al.*, 2013; Po-Chedley *et al.*, 2021). Hence, we assess with *medium confidence* that CMIP5 and CMIP6 models continue to overestimate observed warming in the upper tropical troposphere over the 1979–2014 period by at least 0.1°C per decade,

Notably, despite the accumulation of evidence of excess model warming the IPCC assigns only *medium confidence* to the existence of a warming bias.

5.4 Vertical temperature profile mismatch

Another important model-observational discrepancy is the excess amplification with altitude found in climate models. The comparison was in the IPCC AR5 Chapter 10, although only in the online supplement (Figure 10.SM.1) and only in a figure whose formatting obscured the point. Figure 10.SM.1 is not referenced in the main IPCC report nor in any summary so readers would not have been aware of it. Although not apparent at first glance, it shows that the 1979-2010 warming in the lower troposphere is so small as to be consistent with no GHG forcing at all and is inconsistent with the model runs that do have GHG forcing. In Figure 5.6 we adapt IPCC AR5 Figure 10.SM.1 to draw out this critical point.

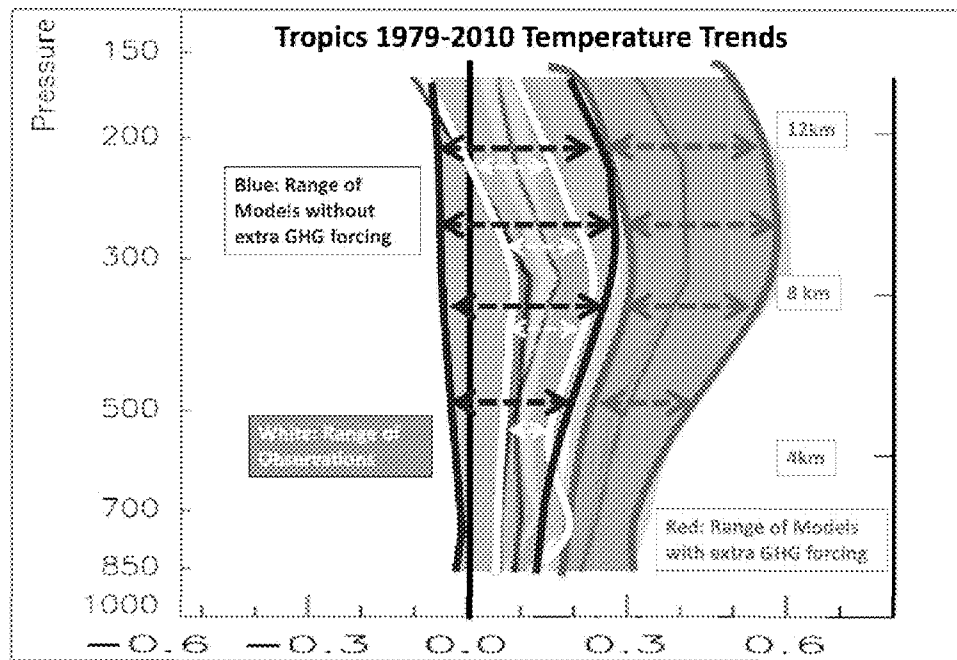


Figure 5.6: Vertical warming pattern for tropics (20S to 20N). Source: Annotated version of IPCC AR5 Figure 10.SM.1

Figure 5.6 compares model and observational temperature trends by altitude between 20S and 20N (the tropics). In this region where the models say the warming should be strongest, the observations (shown here in white) lie within the blue “No CO₂” band and entirely outside the “with CO₂” red envelope. This means that in the entire tropical atmospheric column from the surface to the base of the stratosphere, observed warming trends are so small as to be consistent with the output of models that have no anthropogenic CO₂, and inconsistent with the entire envelope of warming trends generated by models forced with increased CO₂.

A similar comparison is shown in Christy and McNider (2017), an updated version of which (covering 1979-2024) is reproduced as Figure 5.7. Modeled temperature trends exceed observations from the surface through the top of the troposphere, with observed trends below the entire model range at most pressure levels. Also shown in Figure 5.7 is the tropical tropospheric temperature (TTT) average from three satellite data products (NOAA, UAH and RSS) compared to the same layer average from climate models for 1979-2024. Again, the observed trends lie below the entire model range.

The wide range of choices made by modelers to characterize the physical processes in the models (see Box: Climate Modeling in Section 5.1 above) is seen by the large spread of trends in the middle troposphere, ± 40 percent about the median (Fig. 5.7). This vividly illustrates the uncertainties in attempts to model (parameterize) a complex system involving turbulence, moist thermodynamics, and energy fluxes over the full range of the tropical atmosphere’s time and space scales.

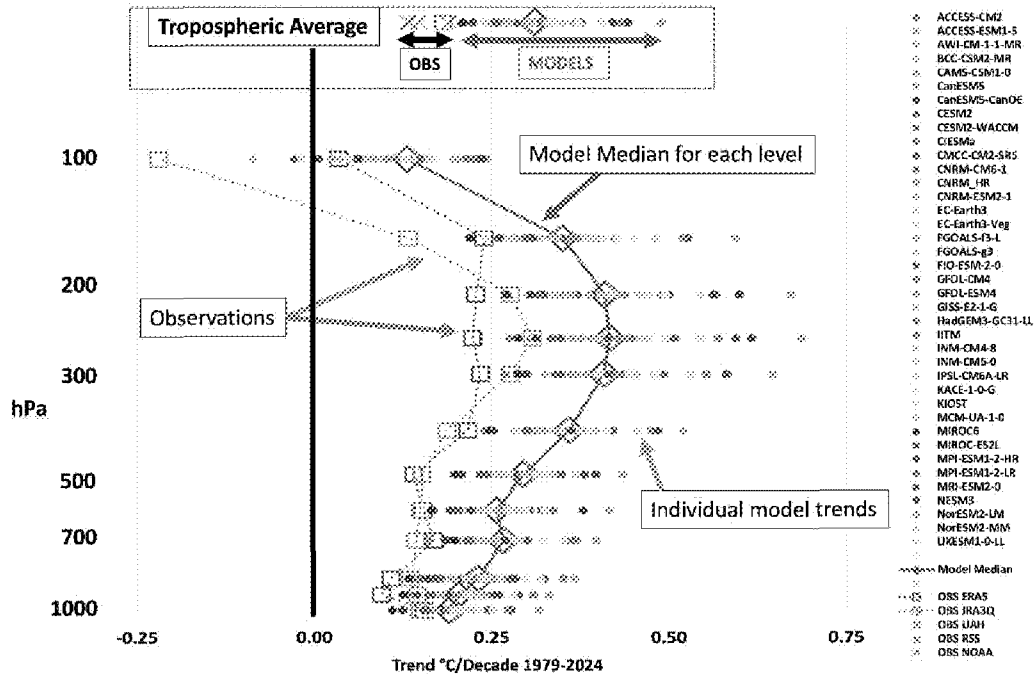


Figure 5.7: Modeled versus observed warming, tropical troposphere. Source: updated from Christy and McNider (2017) including data through 2024. Red line: model average. Green and blue lines: observational series (reanalysis).

This discrepancy has been the source of much controversy, with some arguing that even if there is very little observed warming aloft in the tropics, a “hotspot” still exists in the sense that the warming aloft is greater than at the surface (Santer et al. 2008). But there is good evidence that models also exaggerate the amplification rate. Klotzbach *et al.* (2009), showed that models project greater amplification with altitude than is observed. This result was subsequently confirmed by detailed time series analysis (Vogelsang and Nawaz 2016) which found that the model-observational difference is statistically significant.

The atmosphere’s temperature profile is a case where models are not merely uncertain but also show a common warming bias relative to observations. This suggests that they misrepresent certain fundamental feedback processes.

The IPCC AR6 did not assess this issue.

5.5 Stratospheric cooling

An important element of the expected general “fingerprint” of anthropogenic climate change is simultaneous warming of the troposphere and cooling of the stratosphere. AR6 acknowledged that cooling had been observed but only until the year 2000. The stratosphere has shown some warming since, contrary to model projections.

AR6 WG1 Ch 2 pp. 327-9 states:

Temperatures averaged through the full lower stratosphere (roughly 10–25 km) have decreased over 1980–2019 in all data products, with the bulk of the decrease prior to 2000. The decrease holds even if the influence of the El Chichon (1982) and Pinatubo (1991) volcanic eruptions on the trend,

found by Steiner *et al.* (2020a) to have increased the 1979–2018 cooling trend by 0.06°C per decade, is removed. Most datasets show no significant or only marginally significant trends over 2000–2019, and the results of Philipona *et al.* (2018) show weak increases over 2000–2015 in the very lowermost stratosphere sampled by radiosondes....

It is virtually certain that the lower stratosphere has cooled since the mid-20th century. However, most datasets show that lower stratospheric temperatures have stabilized since the mid-1990s with no significant change over the last 20 years. It is likely that middle and upper stratospheric temperatures have decreased since 1980, but there is low confidence in the magnitude.

The cited source, Philipona *et al.* (2018), in an article entitled “Radiosondes Show That After Decades of Cooling, the Lower Stratosphere Is Now Warming”, stated:

In response to continued greenhouse gas increases and stratospheric ozone depletion, climate models project continued tropospheric warming and stratospheric cooling over the coming decades. Global average satellite observations of lower stratospheric temperatures exhibit no significant trends since the turn of the century. In contrast, an analysis of vertically resolved radiosonde measurements from 60 stations shows an increase of lower stratospheric temperature since the turn of the century at altitudes between 15 and 30 km and over most continents. Trend estimates are somewhat sensitive to homogeneity assessment choices, but all investigated radiosonde data sets suggest a change from late twentieth century cooling to early 21st century warming in the lower stratosphere.

A combination of tropospheric warming and stratospheric cooling is a commonly cited “fingerprint” of anthropogenic warming. Stratospheric warming since 2000 coincides with continued surface and tropospheric warming, a pattern that is not found in climate model simulations and is not apparently consistent with the anthropogenic fingerprint.

5.6 Snow cover mismatch

Data compiled by the Rutgers University Snow Lab show that Northern Hemisphere winter snow cover is not decreasing (Figure 5.8); if anything, it shows an increasing trend.

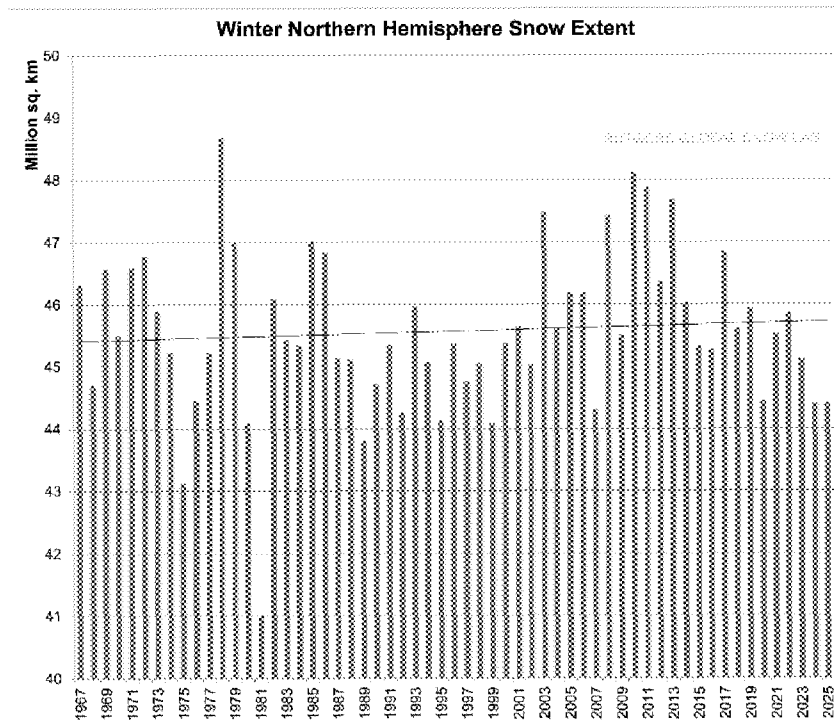


Figure 5.8: Northern Hemisphere Winter Snow extent.

Source: https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhland&ui_season=1
(accessed May 27, 2025)

Yet models project declining Northern Hemisphere snow cover in a warming climate, as described by Connolly *et al.* (2019).

The climate models were found to poorly explain the observed trends [in Northern Hemisphere snow cover]. While the models suggest snow cover should have steadily decreased for all four seasons, only spring and summer exhibited a long-term decrease, and the pattern of the observed decreases for these seasons was quite different from the modelled predictions. Moreover, the observed trends for autumn and winter suggest a long-term increase, although these trends were not statistically significant.

AR6 largely confines its discussion of changing Northern Hemisphere snow cover extent (SCE) to the Spring season, for which models and observations agree on a downward trend. Regarding Winter changes it remarks as follows (AR6 WGI Ch. 2 p. 344):

Assessment of SCE trends in the NH since 1978 indicates that for the October to February period there is substantial uncertainty in trends with the sign dependent on the observational product. Analysis using the NOAA Climate Data Record shows an increase in October to February SCE (Hernández-Henríquez *et al.*, 2015; Kunkel *et al.*, 2016) while analyses based on satellite borne optical sensors (Hori *et al.*, 2017) or multi-observation products (Mudryk *et al.*, 2020) show a negative trend for all seasons.

AR6 WGI Chapter 9 (p. 1284) points out that the NOAA Climate Data Record showing increased fall and winter SCE is inconsistent with land-based observations and model-based data sets. It notes that using optical satellite imagery to infer SCE in winter is challenging due to cloud cover and decreased solar illumination in winter months. Focusing on the Pacific Coast states (CA, OR and WA) cold season mountain snowfall that melts in spring and summer provides a substantial portion of warm season water resources. A comprehensive reconstruction of snowfall for the main source regions (Cascades and Sierra Nevada Mountains) indicates no significant trends in annual totals since the late 19th century (Christy 2022).

In summary, the up-to-date Rutgers SCE database indicates a mismatch between models and observations. Further work to reconcile conflicting trends in observational data sets is required.

5.7 Hemispheric symmetry of the planetary albedo

The planetary albedo is the fraction of incoming solar radiation reflected by the Earth back to space. It is an important element of the radiative energy balance and influences whether the planet will warm or cool over time. The planetary albedo is typically estimated at around 0.30; variations on the scale of 0.01 correspond to changes in solar forcing of about 3 W/m^2 , an amount larger than current anthropogenic forcing. It has long been noted that models disagree with each other and with observations on the value of the global planetary albedo (Stephens *et al.* 2015).

An intriguing property of the Earth's albedo is that, on average, the Northern Hemisphere (NH) and Southern Hemisphere (SH) have had nearly the same albedo, at least throughout the fifty-year satellite record (Stephens *et al.*, 2015). This symmetry is surprising, because the SH has much more ocean than land. Since ocean is less reflective than land, the NH should have higher albedo. Clouds (which are highly reflective) are more common in the NH and so compensate the surface albedo imbalances of the two hemispheres. Datseris and Stephens (2021) show that this cloud compensation comes from the extra-tropical storm tracks of the SH, which are cloudier than those of the NH. While the mechanism for this hemispheric symmetry is unclear, it likely operates on large temporal and spatial scales.

The hemispheric symmetry of the albedo is a simple gross metric for climate models. Rugenstein and Hakuba (2023) defined that metric as the difference between the NH and SH annual mean albedos, expressed as Wm^{-2} of the reflected sunlight, and compiled it for the CMIP6 climate models, as shown in Figure 5.9. Most of the CMIP6 models do not reproduce the small observed asymmetry (about 0.1 Wm^{-2}) and even disagree as to which hemisphere is more reflective. Moreover, the magnitude of the asymmetry ranges up to 5 Wm^{-2} in some models, twice as large as the current anthropogenic forcing (about 2.5 Wm^{-2}).

The significance of unphysical albedo asymmetries in the climate models is not yet fully known. However, other model studies suggest that interhemispheric changes in albedo can alter poleward heat fluxes, meridional temperature gradients, storminess, and differences in hemispheric ocean heat storage. The discrepancy between models and observations further raises issues regarding cloud feedback processes and so more generally diminishes confidence in model projections of the future climate.

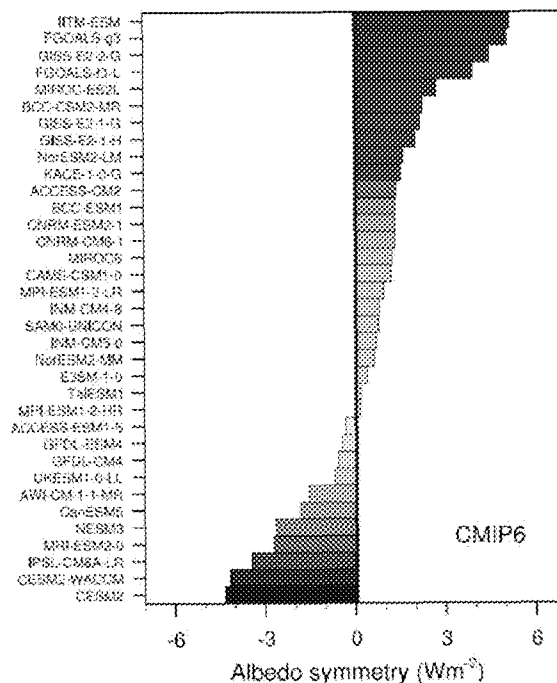


Figure 5.9. Differences in 20-year average reflectivity (albedo) between the Northern and Southern Hemispheres for CMIP6 models used in the most recent IPCC assessment (colored bars). The very small observed difference is indicated by the vertical black line. From Rugenstein and Hakuba (2023).

5.8 U.S. Corn Belt

One of the largest discrepancies between models and observations is in the U.S. Corn Belt, a region of particular importance to global food production. Figure 5.10 shows the warming trends for summertime (June, July, August) for the 12-state Corn Belt (IN, IA, IL, ND, SD, MO, MN, WI, MI, OH, KS, NE) during 1973-2022. All 36 climate models (red) warm far too rapidly compared to observations (blue).

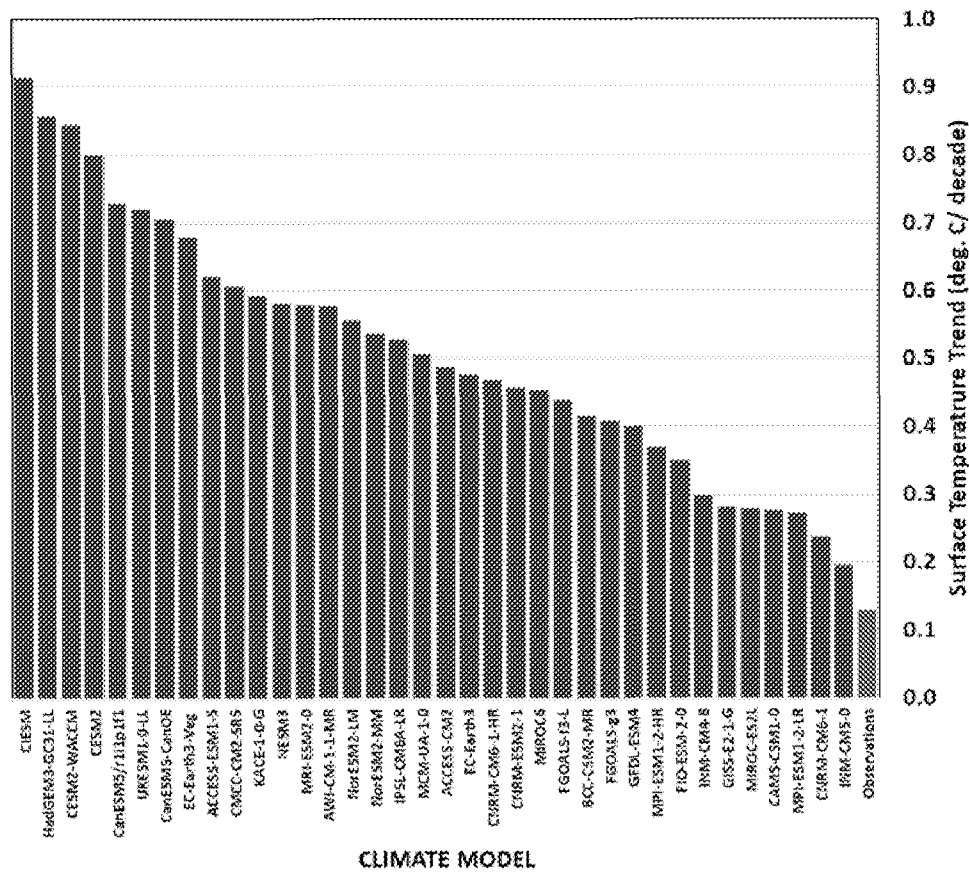


Figure 5.10: Modeled versus observed warming trends in the U.S. Corn Belt, 1973-2022.

As discussed in Chapter 9, the anticipated negative effects of increasing temperatures on U.S. corn yields have not materialized, in contrast to widely publicized studies proclaiming that theoretical future impacts are already being experienced (*e.g.*, Seager *et al.*, 2018).

The IPCC acknowledges limitations in the accuracy of regional climate model outputs. This example shows that users need to assess model projections carefully on a case-by-case basis since local biases might be sufficiently large that the models are simply not fit for purpose. As has recently been noted by two leaders of the modeling community (emphasis added)

... for many key applications that require regional climate model output or for assessing large-scale changes from small scale processes, we believe that **the current generation of models is not fit for purpose**. (Palmer and Stevens 2019)

To summarize:

- Climate models show warming biases in many aspects of their reproduction of the past few decades.
- They produce too much warming at the surface (except in the models with lowest ECS), too much warming in the lower-and mid-troposphere and too much amplification of warming aloft
- They also produce too much stratospheric cooling, too much snow loss, and too much warming in the U.S. Corn Belt.

- The hemispheric albedo difference in individual climate models ranges widely in sign and magnitude compared to observations. The range in W/m^2 is three times larger than the direct anthropogenic forcing of CO_2 .
- The IPCC has acknowledged some of these issues but not others.

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6 EXTREME WEATHER

Chapter Summary

Most types of extreme weather exhibit no statistically significant long-term trends over the available historical record. While there has been an increase in hot days in the U.S. since the 1950s, a point emphasized by AR6, numbers are still low relative to the 1920s and 1930s. Extreme convective storms, hurricanes, tornadoes, floods and droughts exhibit considerable natural variability, but long-term increases are not detected. Some increases in extreme precipitation events can be detected in some regions over short intervals but the trends do not persist over long periods and at the regional scale. Wildfires are not more common in the U.S. than they were in the 1980s. Burned area increased from the 1960s to the early 2000's, however it is low compared to the estimated natural baseline level. U.S. wildfire activity is strongly affected by forest management practices.

6.1 Introduction

High impact weather extremes, usually related to temperature, precipitation and/or high wind, can disrupt infrastructure and therefore endanger human health and wellbeing. The issue is not whether extremes occur. Rather, it is whether there are long-term (decadal scale) changes in the frequency or character of extremes (“detection”), as well as the extent to which such changes and the attendant changes in hazards are caused by anthropogenic emissions of greenhouse gases (“attribution”; e.g., AR6 Seneviratne *et al.* 2021).

It is naïve to assume that any recent extreme event is caused by human influences on the climate. Climate is about the statistical properties of weather over decades, not single events. Further, there are only about 130 years of reliable observational records that can be analyzed statistically. That brief interval does not begin to contain all the extreme events that the climate system can create on its own. Over geologic time the climate system has generated an (essentially) infinite variety of weather patterns and extremes that humans have never observed and thus are absent from the databases used to determine extreme statistics [see *Perils of short data records* below]. For that reason, attributing an extreme event unprecedented in the record requires assumptions about the magnitude of natural variations.

This chapter is concerned with detection of trends in extreme weather, while Chapter 8 considers causal attribution, with Section 8.4 specifically addressing extreme weather. If no trend is detected, then clearly there is no basis for attribution. But even where a trend is observed, attribution to human-caused warming does not necessarily follow.

This is especially true for precipitation events. The hydrological literature has long noted the phenomenon of Long-Term Persistence (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2016). LTP has a formal mathematical definition, but it can be thought of as the presence of natural variations with strong autocorrelations that result in cycle-like behavior on long time scales. The presence of LTP requires long records to accurately estimate variability. Analysis of records that are short relative to the LTP scale will tend to underestimate variability, therefore overstating the significance of apparent trends and underestimating the likelihood of extreme events (Cohn and Lins 2005).

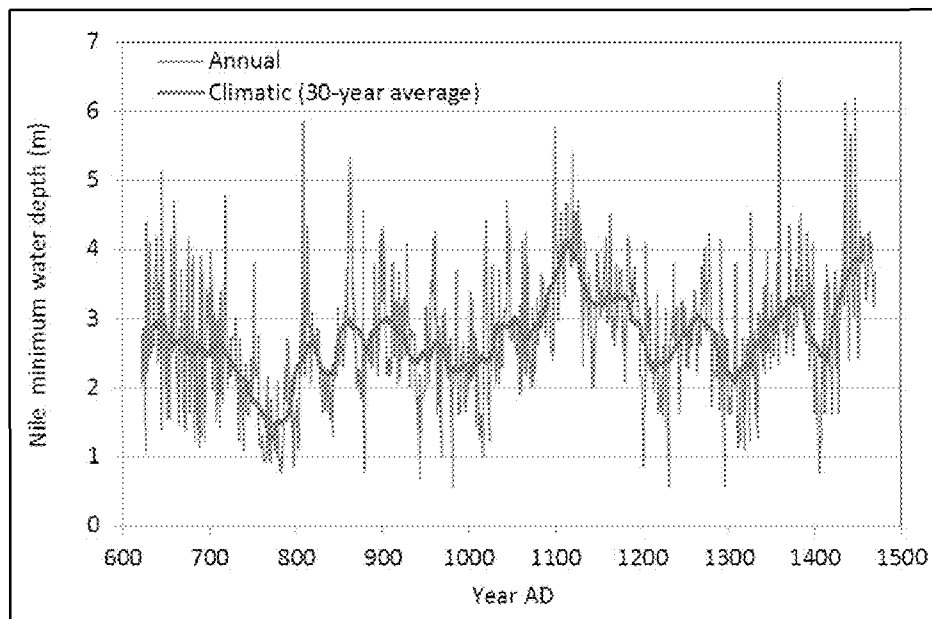


Figure 6.1.1: The annual minimum depth of the Nile River near Cairo over more than 650 years from 622 to 1284 A.D. The data, measured in meters, shows a characteristic pattern of year-to-year fluctuations around longer-term trends. Data from Koutsoyiannis (2013)

A good example of LTP is the eight-century long record of the annual minimum height of the Nile River observed at Roda Island in Cairo shown in Figure 6.1.1. The Nile River is fed by precipitation over a 4 million square mile drainage basin, an area equal to about one third of CONUS. Since human influences on the global climate were negligible before the 20th century, the century-scale variability of the thirty-year average is entirely natural; Egyptians of the seventh and eight centuries would have been incorrect to assume that the worsening drought during that time was the “new normal.”

With these caveats in mind, we examine the evidence for changes in selected weather and climate extremes. A recurring theme is the wide gap between public perceptions and scientific evidence. It has become routine in media coverage, government and private sector discussions, and even in some academic literature to make generalized assertions that extreme weather of all types is getting worse due to GHGs and “climate change.” Yet expert assessments typically have not drawn such sweeping conclusions and instead have emphasized the difficulty both of identifying specific trends and establishing a causal connection with anthropogenic forcing.

In the sections to follow we provide excerpts from various IPCC and NCA assessment reports denoting the sources as follows:

SREX: The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2012)

AR6: The IPCC Sixth Assessment Report Working Group 1 (2021).

NCA4: The U.S. Climate Science Special Report of the Fourth National Climate Assessment (2017) Volume I.

NCA5: The U.S. Climate Science Special Report of the Fifth National Climate Assessment (2023) Volume I.

In the excerpts, *italics* are in the original whereas **boldface** emphasis has been added.

Additionally we present updated data series from standard government sources to provide up-to-date information through 2024 wherever possible.

6.2 Hurricanes and tropical cyclones

AR6 provides the following assessment of tropical cyclones (TCs; used here as a synonym for hurricanes):

AR6: There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (IPCC, 2021 p. 1585)

AR6: It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades . . . There is *low confidence* in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. (IPCC, 2023 SPM p. 9)

AR6: A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows **no trend in the frequency of U.S. landfall events**. (IPCC 2021 p. 1585)

Since 1980, when satellite observations first fully covered the global oceans, we have confidence in the numbers of total global hurricanes and major hurricanes (Category 3 and higher). Figure 6.2.1 shows that on average, each year there are about 50 hurricanes, with about 25 reaching major hurricane status (Maue, 2025). There is substantial year-to-year and decadal variability, a weak decrease in the number of hurricanes, and a slight but insignificant increase in the number of major hurricanes. These two trends combine to create an overall increase in the proportion of major hurricanes.

Global hurricane statistics are dominated by the Northwest Pacific Ocean, which accounts for ~35 percent of total global hurricanes, whereas the Atlantic accounts for ~15 percent of global hurricanes (Colorado State University, 2025). Data in the Atlantic basin extends further back than in the other ocean basins and is most relevant to U.S. policy makers.

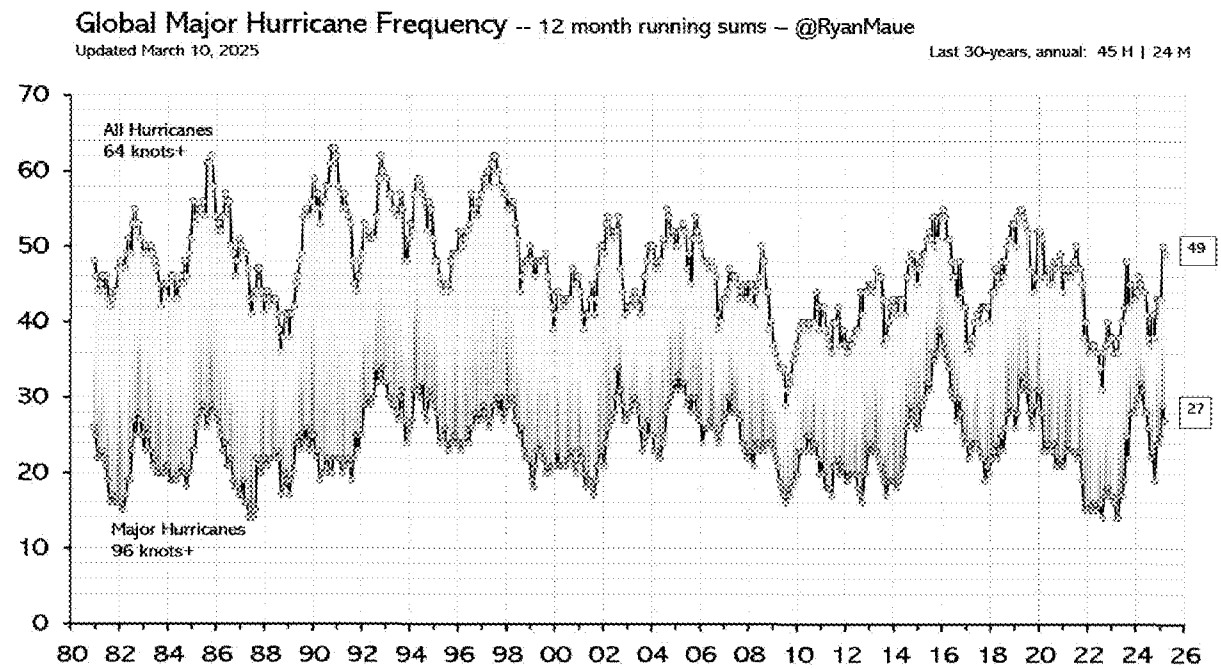


Figure 6.2.1: Global frequency of hurricanes and major hurricanes since 1980.

Figure 6.2.2 shows the frequency of Atlantic hurricanes and major hurricanes (Category 3 and higher) back to 1920. Data prior to 1965 (the onset of satellite observations in the Atlantic, shaded in blue) shows some undercounting, with data prior to 1920 showing substantial undercounting (Vecchi and Knutson, 2011). All measures of Atlantic hurricane activity show a significant increase since 1970. However, the period from 1971-1994 saw exceptionally low activity, with high activity (comparable to the past two decades, even with undercounting) also observed during the 1950's and 1960's, and even in the 1930's.

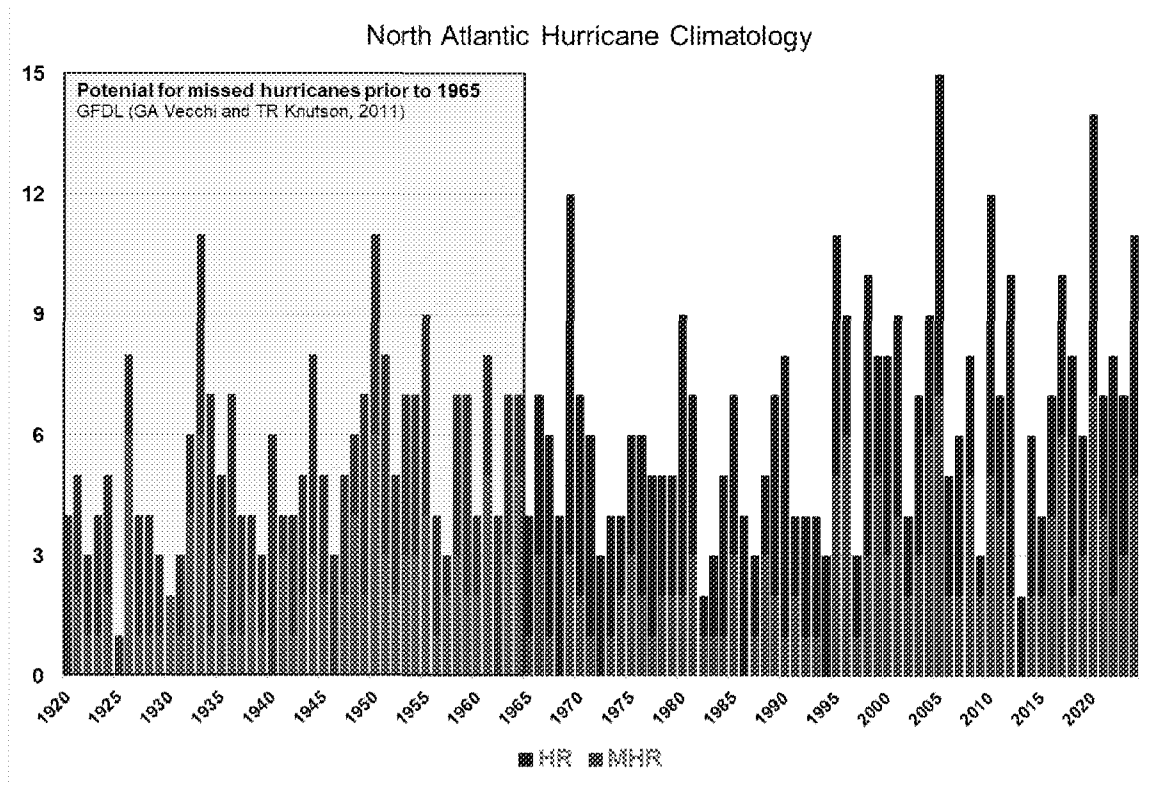


Figure 6.2.2: Atlantic frequency of hurricanes (HR) and major hurricanes (MHR) since 1920. Source National Hurricane Center (2024)

Figure 6.2.2 shows that Atlantic hurricanes vary strongly on decadal and multidecadal time scales. These variations are associated primarily with the Atlantic Multidecadal Oscillation (AMO), which is manifest in basin-wide sea surface temperature and sea level pressure fluctuations connected to large scale ocean circulation patterns. The AMO was in its warm phase during 1926-1970 and 1995-present, but in its cool phase during 1971-1994. It has its greatest impact on the number of major hurricanes (Category 3+), identified by Goldenberg *et al.* (2001) as associated with above normal SSTs and decreased vertical shear in the AMO warm phase (see also Bell and Chelliah, 2006; Klotzbach *et al.*, 2018).

Klotzbach *et al.* (2018) conducted a comprehensive evaluation of the landfalling hurricane data for the Continental U.S. since 1900. Figure 6.2.3 updates their analysis through 2024. While the largest numbers of landfalling hurricanes are from 2004, 2005 and 2020, there is no statistically significant trend since 1920. Figure 6.2.3 also shows the time series for major hurricane landfalls (Category 3-5). The largest year in the record is 2005, with 4 major hurricane landfalls. However, following 2005 there were no major hurricanes striking the U.S through 2016, the longest such period since 1920.

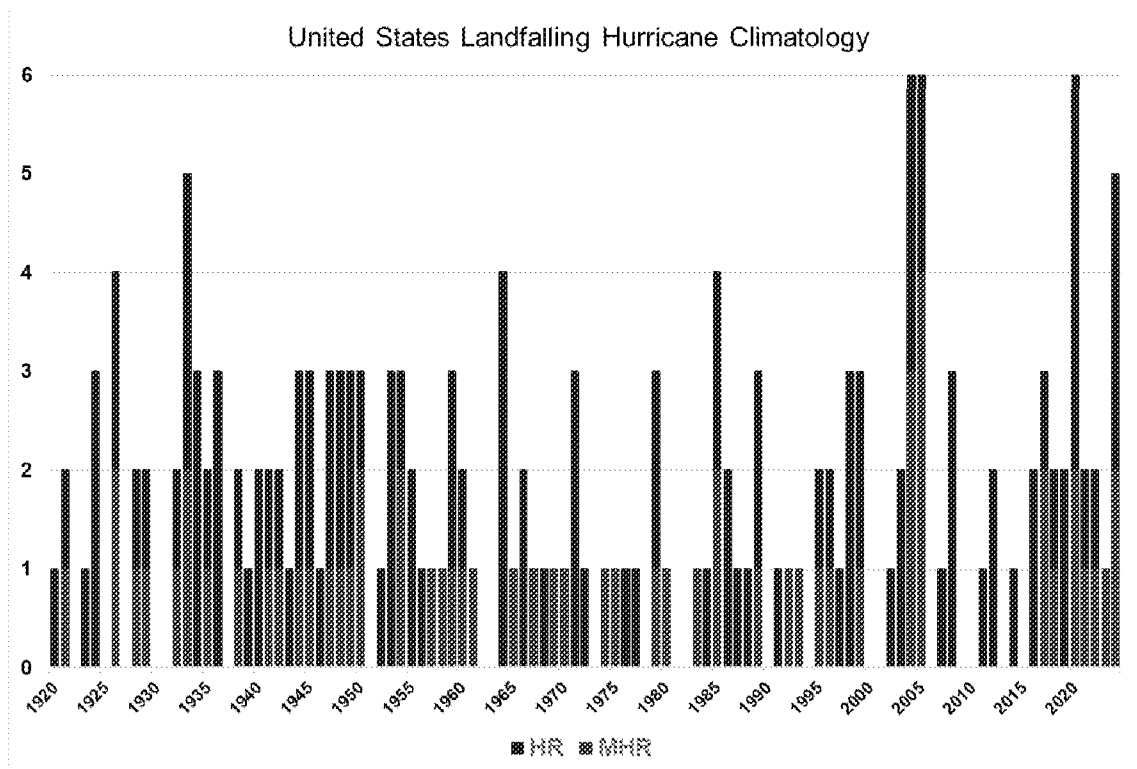


Figure 6.2.3: U.S. landfalling frequency of hurricanes (HR) and major hurricanes (MHR) since 1920. Source NOAA HRD(a) (2024)

Figure 6.2.3 shows substantial interannual to multidecadal variability in U.S. landfall activity. Klotzbach *et al.* (2018) examined how the landfall counts vary with ENSO (El Niño versus La Niña) and the warm versus cold phases of the Atlantic Multidecadal Oscillation (AMO).

Villarini *et al.* (2012) provide an analysis of U.S. hurricane landfalls back to 1878. While it is possible that some landfalls were missed in the late 19th century owing to sparsely populated regions on the Gulf Coast, it is remarkable that the highest year in the entire record is 1886, with 7 hurricane landfalls, when human influences on the climate were much smaller than they are today.

Table 6.2.1 shows the 10 strongest hurricanes (plus ties) to make U.S. landfall. Of the hurricanes that have made landfall with sustained winds greater than 150 mph, only one has occurred in the 21st century.

In summary, analyses of both global and regional variability and trends of hurricane activity provide the basis for detecting changes and understanding their causes. The relatively short historical record of hurricane activity, and the even shorter record from the satellite era, is not sufficient to assess whether recent hurricane activity is unusual relative to the background natural variability. Atlantic hurricane processes are influenced substantially by the natural modes of ocean circulation variability in the Atlantic, notably the Atlantic Multidecadal Oscillation. While it has long been hypothesized that a rising global sea surface temperature would cause an increase in hurricane intensity, identification of any significant trend in the hurricane data is hampered by a short data record and substantial natural variability.

Rank	Year	Landfall Wind (MPH)	Name
1	1935	185	"Labor Day"
2	1969	175	Camille
3	1992	165	Andrew
4	2018	160	Michael
5	1856	150	"Last Island"
5	1886	150	"Indianola"
5	1919	150	-----
5	1932	150	"Freeport"
5	2004	150	Charley
5	2020	150	Laura
5	2021	150	Ida
5	2022	150	Ian

Table 6.2.1 Strongest hurricanes to make landfall along the U.S. coast. Source (NOAA HRD(b), 2024)

6.3 Temperature extremes

The AR6 assessment focused on the period after 1950 and reported increasing trends in heatwave frequency and intensity. However, NCA4 noted that heatwave activity in the U.S. reached a peak in the 1930s (Figure 6.3.1).

AR6: It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe (SPM, A3.1)

AR6: In North America, there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, while there are more contrasting trends in the annual maximum daily temperatures in parts of the USA. (Chapter 11, p 1550)

NCA4: Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year **increased** in some parts of the West over the past century, but there were **decreases** in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net **decrease**, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). (pp. 190-191)

NCA4: Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, **heat wave magnitude reached a maximum in the 1930s.** (pp. 190-191)

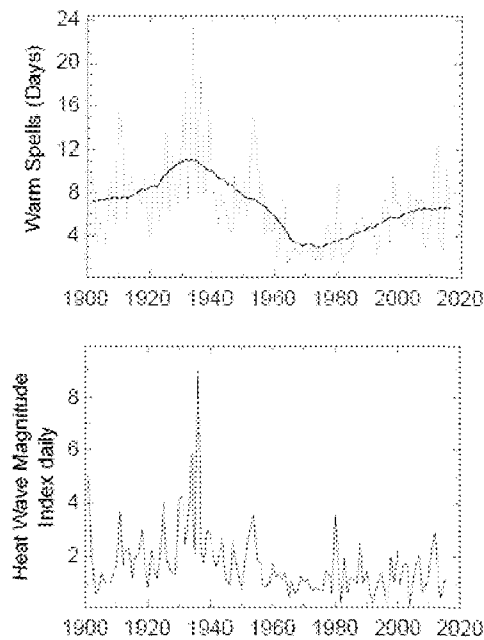


Figure 6.3.1: U.S. Heat waves since 1900. Source: NCA4 Figure 6.4

6.3.1 Temperatures in the U.S. are becoming less extreme

Daily maximum temperatures in the warm season (Tmax, May-Sep) and daily minimum temperatures in the cold season (Tmin, Dec-Mar) are available beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (see Figure 6.3.2; Quinlan *et al.* 1987, Karl *et al.* 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves, and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors in the dataset, including unresolved spurious warming due to UHI effects that especially bias Tmin records, this data set is sufficiently accurate for assessing trends in Tmax heat extremes.

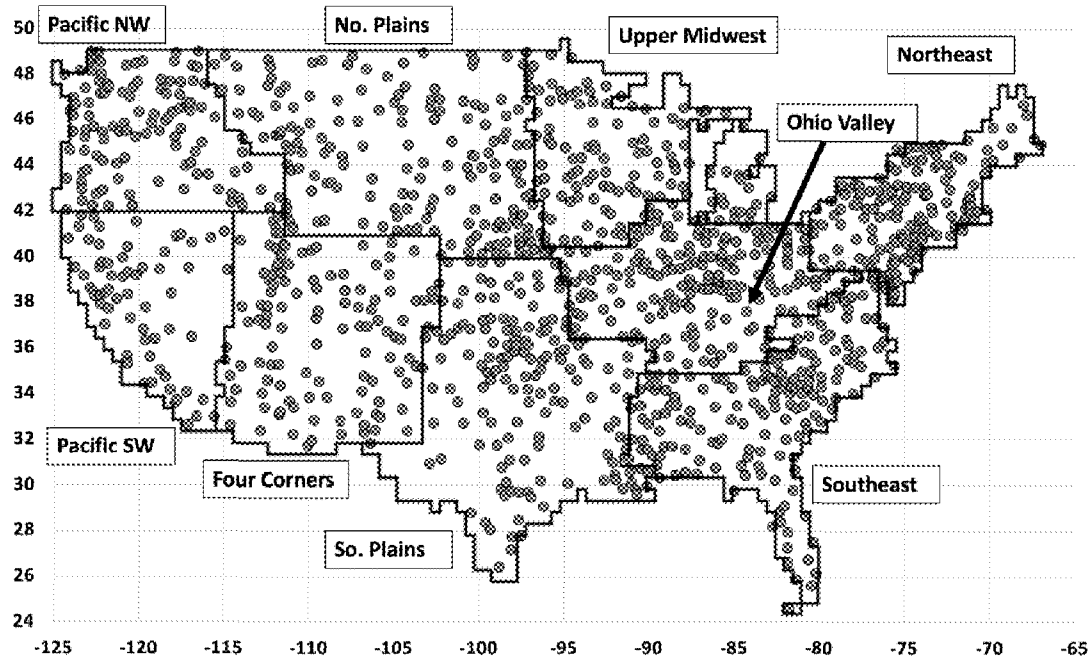


Figure 6.3.2 Locations of USHCN temperature stations. Source: USHCN.

We begin with the question of whether the occurrence of daily record high or low temperatures has changed since Dec 1898. Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each station and day, we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for Tmax would be 1.21 ($=153/126$) per station per year and for Tmin 0.96 ($=122/126$) per station per year.

Figure 6.3.3 shows the observed distribution in time of the occurrence of these extreme events. There is a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60 percent of the Tmax records and 59 percent of the Tmin records occurred in the first half of the period (1899-1961).

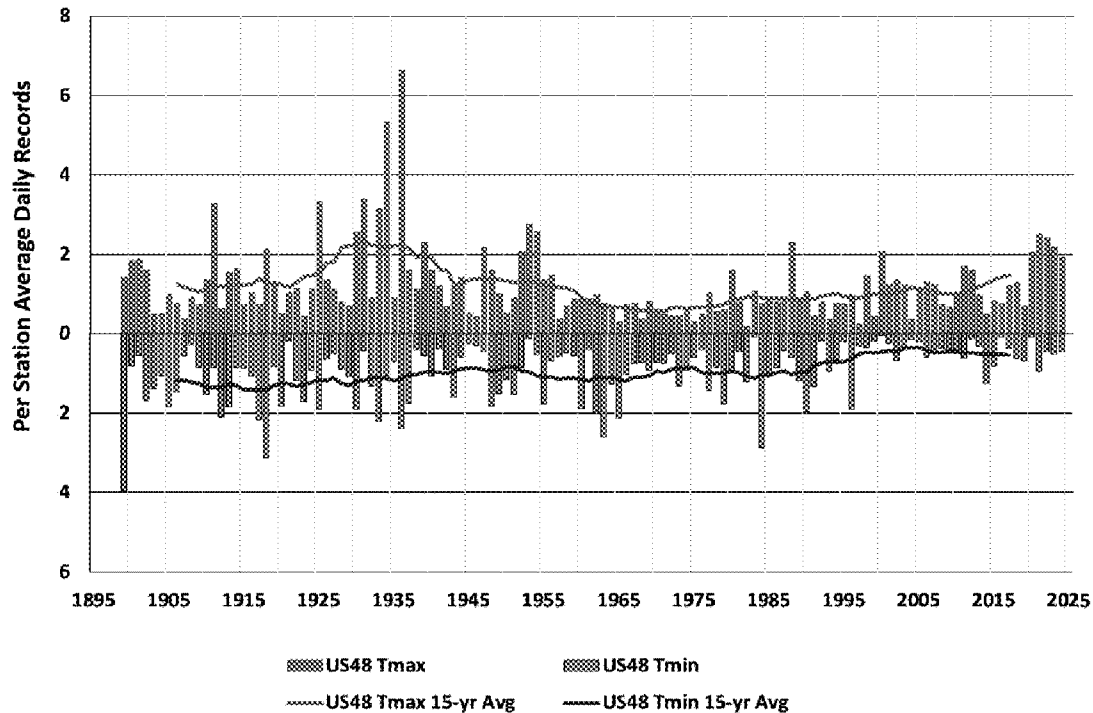


Figure 6.3.3 Number of daily record High (red) and Low (blue) temperatures for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92 percent of observations in the 126-year period since Dec 1898. US48: contiguous U.S. states. Tmax: maximum temperature. Tmin: minimum temperature.

On the cold side, the Valentine's Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced by CONUS, with 1917 in 2nd place. The frequency of cold records has declined, especially over the last quarter of the period in which only 13 percent of the extreme cold events were measured. In contrast, 25 percent of the extreme Tmax records were achieved in the last quarter, in accordance with statistical expectations. These general features have been noted in past assessments (see above, IPCC AR6, NCA4). Combining the two histories, the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 6.3.4. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated. Then the differences between these were computed by station and geographically-averaged over all stations, thus yielding an annual measure of the expected range of local extreme temperatures for each year. Figure 6.3.4 shows the 15-year trailing average of this measure, which has clearly declined over the past century.

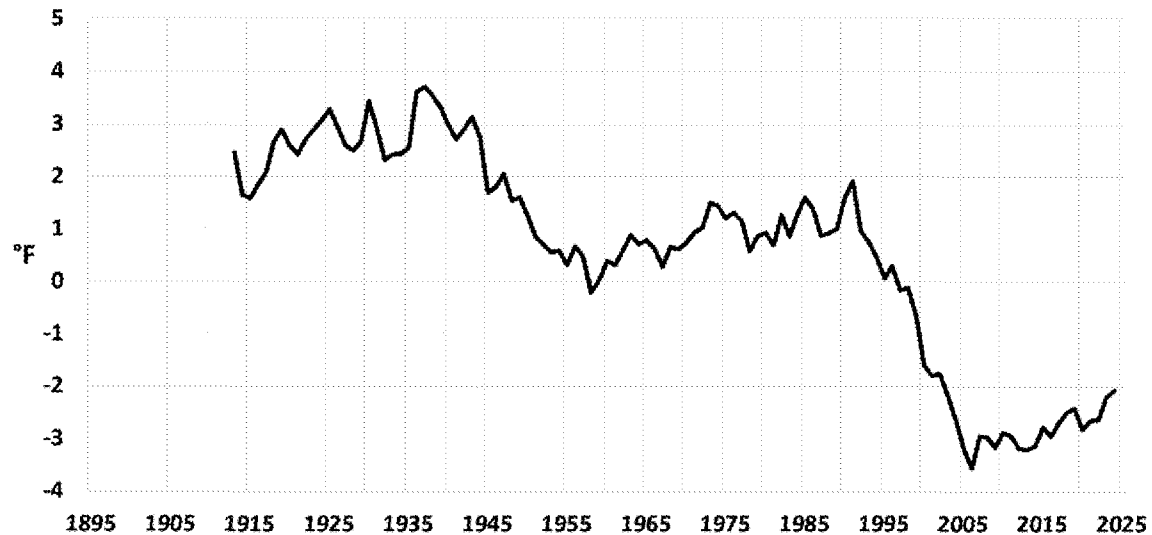


Figure 6.3.4. 15-year trailing average of the difference each year of each station's hottest warm-season Tmax and coldest cold-season Tmin relative to the long-term average. Source: Author analysis of USHCN data.

The average difference for each station between the hottest summer Tmax and coldest winter Tmin has declined by about 5°F in the past 126 years. The decline is due mostly to warmer winter Tmin, but a decline in summer Tmax is also a factor. The rise in Tmin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (the so-called urban heat island effect; Section 3.3 and Spencer *et al.* 2025).

In summary, while temperature extremes are regularly experienced in the U.S. and attract a great deal of media attention, long term records show the U.S. climate has become less extreme over time (milder) when measured by the range between warm season maxima and cold season minima.

6.3.2 Exceedances of a heat threshold

Under the heading of “The Risk of Temperature Extremes is Changing”, the most recent U.S. National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating,

The western U.S. has been particularly affected by extreme heat since the 1980s ..., experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the U.S. since 2018, including a record-shattering event in the Pacific Northwest in 2021.

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations that have near 95°F Tmax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F Tmax temperatures, a small change will not have much impact on the results.

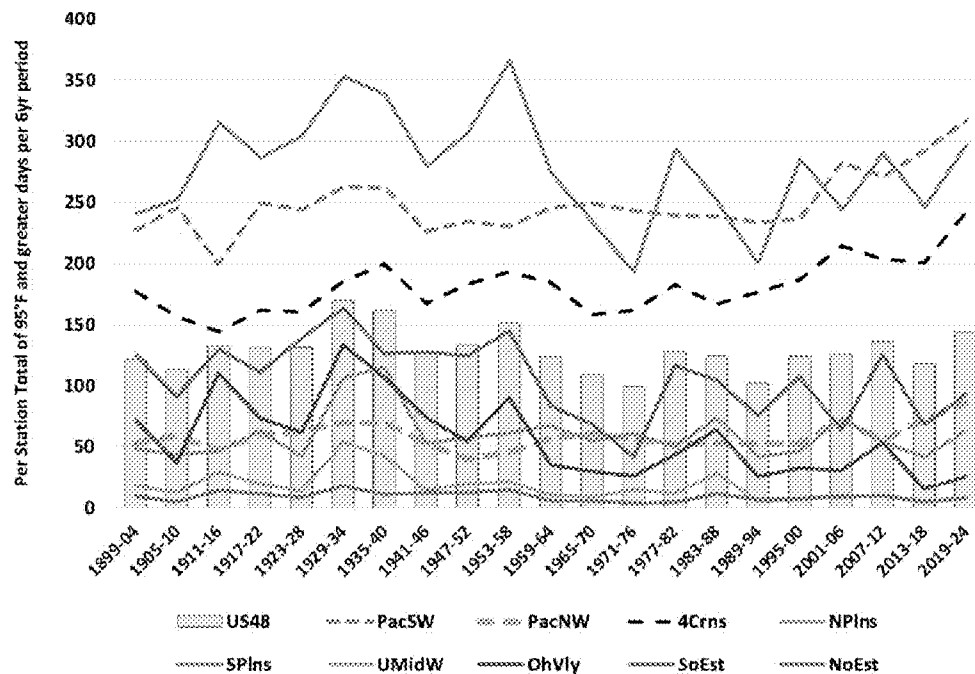


Figure 6.3.5. Total number of days $\geq 95^{\circ}\text{F}$ in 6-yr periods, U.S. 48 (bars) and regions (lines). A 6-year period is used as this evenly divides the 126-year record. US48: contiguous U.S. states. See Figure 6.3.2 for region names. Source: Author analysis of USHCN data.

In the past 126 years, the average CONUS station experienced 129 days exceeding 95°C per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, such threshold analyses must be interpreted with caution. Figure 6.3.5 shows that only three of the nine regions, all in the West, have experienced upward trends in the number of 95°F or hotter days (dashed lines). The CONUS as a whole has not, and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 referenced in the NCA5 quote will be examined more closely in Section 8.6.1. The evidence indicates that it was a single, unprecedented event in the record, not part of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was $+10.8^{\circ}\text{C}$, the most extreme Northern Hemisphere grid point summer anomaly in the 46 years from over 4 million grid values. In contrast, the global temperature anomaly during that time was virtually zero ($+0.03^{\circ}\text{C}$, Mass *et al.* 2024).

The NCA5 heading “The Risk of Temperature Extremes is Changing” suggests pervasive positive trends are now being observed in threshold temperatures, but that is not evident in the figures above.

6.3.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than a single daily record temperature. We measure “Heatwave Days” here as the count of all days in May-Sep each year that exceed the 90th percentile for that day and that lie within a period of at least six consecutive days. This is equivalent to the method used in NCA4, except that the reference period here is the entire record 1899-2024 while NCA4 truncated the reference period to 1961-1990, which was a cool interval. That truncation boosts positive results (days exceeding the 90th percentile) in years warmer than the reference period, especially starting in 1960 and moving to the present (see Figure 6.3.6 and discussion below).

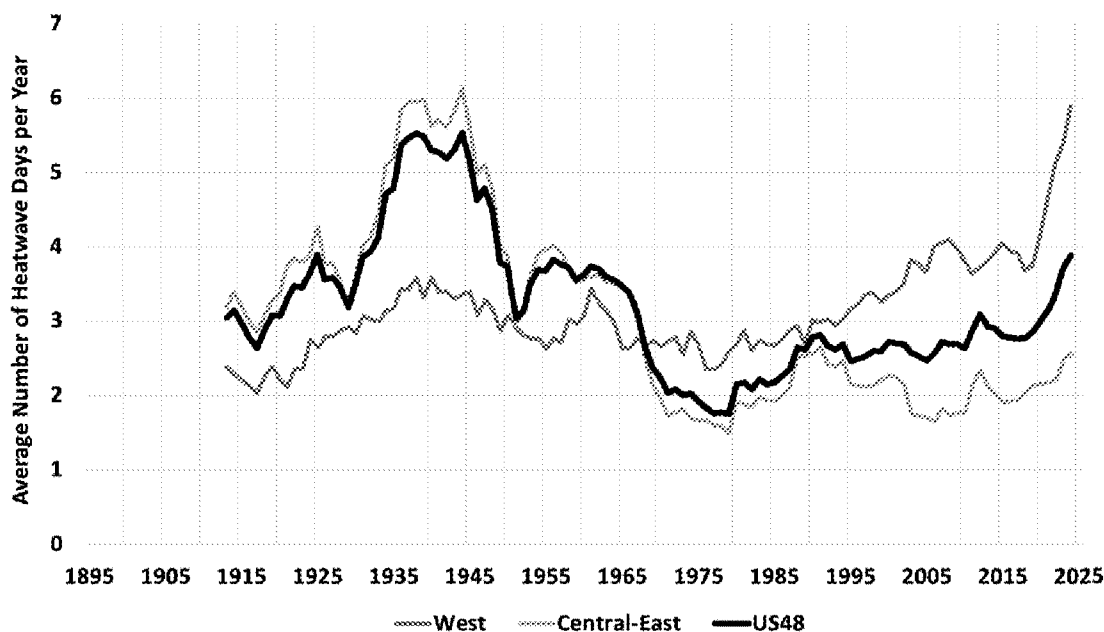


Figure 6.3.6 15-year trailing average of number of heatwave days per year per station in the CONUS (black line) and two regions: West (red), Central-east (green).

Figure 6.3.6 indicates that there are regional variations in heatwave activity. The excessive heat of the first half of the 20th century occurred primarily in the eastern two-thirds of the nation, while the West has seen a recent increase of heatwave days (NCA5). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20th century, but in the 21st century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago, consistent with the upper panel of our Figure 6.4.1 taken from NCA4.

This metric varies significantly with region. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

The analysis of heatwaves is an example of why it is important to consider complete datasets and appropriate metrics. The NCA5 directs readers to the website <https://www.globalchange.gov/indicators/heat-waves> (USGCRP 2023) to view a figure showing the number of urban heatwaves by decade from the 1960s, which we reproduce as Figure 6.3.7.

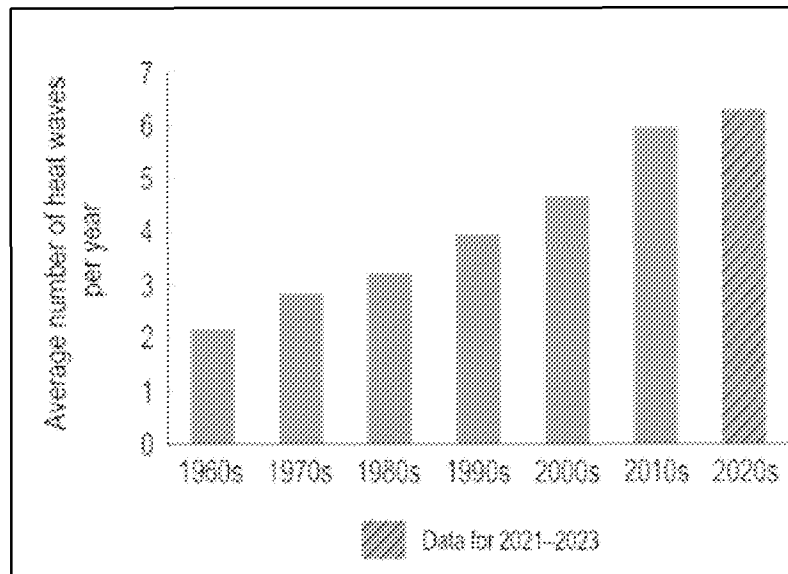


Figure 6.3.7: Average number of urban heatwaves per year for 50 large U.S. metropolitan areas, a misleading metric for reasons explained in the text. From <https://www.globalchange.gov/indicators/heat-waves> (accessed May 22, 2025).

The figure shows a monotonic increase in each decade from two occurrences per year in the 1960s to six in the 2020s. The definition of a heatwave used is an unusual but practical measure of human discomfort - a period of at least 2 consecutive days when the *minimum* apparent temperature (combination of temperature and humidity) exceeds the 85th percentile. Note too, the dataset is limited to the 50 largest U.S. cities.

Given the unusual heatwave definition and urban focus, these increasing values since 1960 presented in USGCRP (2023) are not informative about long term trends or the influence of GHG emissions for at least two reasons. First, as shown in Figures 6.3.1 and 6.3.6, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. Second, post-1960 urbanization in these cities is a major factor in the rise of Tmin relative to co-located Tmax and relative to Tmin at nearby rural stations. This does not dismiss the real rise in nighttime temperatures in major U. S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons that summer Tmax (especially in rural areas) is a better metric for detecting changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy *et al.* 2009). For CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves against the background of urbanization and natural climate variability.

6.4 Extreme precipitation

AR6 assessed that an increase in heavy precipitation has been observed in data starting in the 1950s.

AR6: The frequency and intensity of **heavy precipitation events have increased** since the 1950s over most land area for which observational data are sufficient for trend analysis (high confidence). (SPM A3.2)

AR6: In North America, there is robust evidence that the **magnitude and intensity of extreme precipitation has very likely increased** since the 1950s. Both [one-day maxima] and [5-day maxima] have significantly increased in North America during 1950-2018. (Chapter 11, p. 1560)

The U.S. National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of CONUS, especially the Northeast, when starting the analysis in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme precipitation events are in the Northeast and the smallest in the West, a pattern counter to the changes in temperature extremes (Figure 6.3.6).

McKittrick and Christy (2019) examined long-term and consistent station observations of extreme daily precipitation to test some of these NCA claims for the Southeast and West Coast using a trend model with a non-parametric variance estimator robust to the complex autocorrelation properties of precipitation data. When the time series were extended back in time (as far as 1872 in some cases) or started later (1978), there were no significant trends for either region.

These findings have been updated for this report (McKittrick and Christy 2025) with similarly constructed observations from 29 stations on the CONUS Pacific Coast (1893ff from San Diego CA to Blaine WA) and 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC), also adding 27 stations in the Northeast (1888ff from Buffalo NY to Eastport ME). The locations are shown in Figure 6.4.1. The stations were selected based on availability of long-term high-quality records. The regions are each associated with important features of extreme precipitation behavior: the Pacific coast is associated with landfalling atmospheric rivers for which AR6 cites evidence of increasing activity since 1948 with further increases expected as the world warms (AR6 8.3.2.8.2); the NCA report indicates that the Northeast has experienced the greatest increase in extreme events, and the Southeast is also a place noted in the NCAs as having increased extreme events.

The results of applying the analysis of McKittrick and Christy (2019) were as follows for each region, then followed by further explanation.

Pacific Coast heavy rainfall events

- The average precipitation trend is statistically significant (downwards) in Astoria OR; insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Big Sur CA; insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Aberdeen WA and Big Sur CA and negative and significant in Newport OR (insignificant elsewhere).
- Averaged over all stations in the region, none of these three trend parameters is statistically significant.

The Pacific Coast receives considerable precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov *et al.* 2017, Pan *et al.* 2024). The worst series of such events in recent history was the so-called ARkStorm that occurred during December 1861 and January 1862; it dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Null and Hulbert 2007). Additionally, Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1800 years, occurring at intervals of 300 years or so (Porter *et al.* 2011).

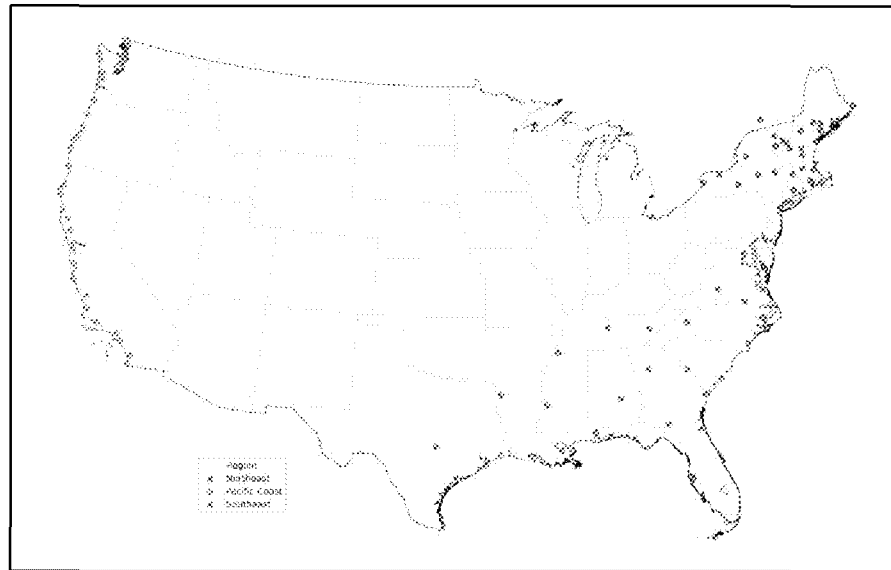


Figure 6.4.1: Locations of precipitation monitoring stations used in this report. Orange: Pacific coast. Blue: Northeast. Green: Southeast. Data from McKittrick and Christy (2025).

We examine occurrences of 5-day deluges as follows. Taking the Pacific coast as an example, a 130-year span contains 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values across the sample. A single year might have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5yr events. If there are no trends in precipitation, then the total number of these events across all stations should be evenly spread over the years. In Fig. 6.4.2 we show the distribution in time of these events for the Pacific coast. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of such precipitation metrics, there is no indication of a tendency to become more frequent over time.

Southeast heavy rainfall events

- The trend in average precipitation is positive and statistically significant in Mobile AL and Quitman GA but insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Mobile AL but insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Vicksburg MS and Norfolk VA but insignificant elsewhere.
- Averaged over all stations in the region none of these three trend parameters is statistically significant

Figure 6.4.3 is analogous to Figure 6.4.2 for the last 150 years in the Southeast humid zone. The temporal pattern of 5-day totals of the 1-in-5yr heavy events is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 -- an increasing frequency of heavy events due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.

BOX: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 7.2.

Event	Record (inches)	Year
3-day	6.94	2023
5-day	8.55	2023
14-day	12.62	2023
30-day	18.93	1998

Table 6.2: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent years. 2023 appears to be an exceptional year and since it is near the end of the sample, it might suggest that the climate has shifted into a more hazardous state, perhaps because of human influences. [Note “2023” indicates the event occurred in the water-year of Aug 2022 to Jul 2023.]

But the picture is very different if we use a sample that begins 45 years earlier, in 1850. Table 6.3 shows that the record-setting events all happened in the 1860s. Furthermore 2023 is now not even in 2nd place but falls to 3rd or 4th place. And comparing the records of the two charts shows the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

Event	Record (inches)	Year	Rank of 130-yr extreme listed in Table 6.2
3-day	8.85	1867	3
5-day	9.80	1867	3
14-day	19.05	1862	4
30-day	28.25	1862	2

Table 6.3: Extreme rainfall records, San Francisco, 1850-2024.

The range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter *et al.* (2011) discovered that in the past 1,800 years at least six megastorms were more intense than the devastating 1861-62 ARkStorm that struck the region. Evidently such extreme events, “unprecedented” in our 1895-2024 sample, have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (Section 8.6). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50 percent determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own, even without human influences.

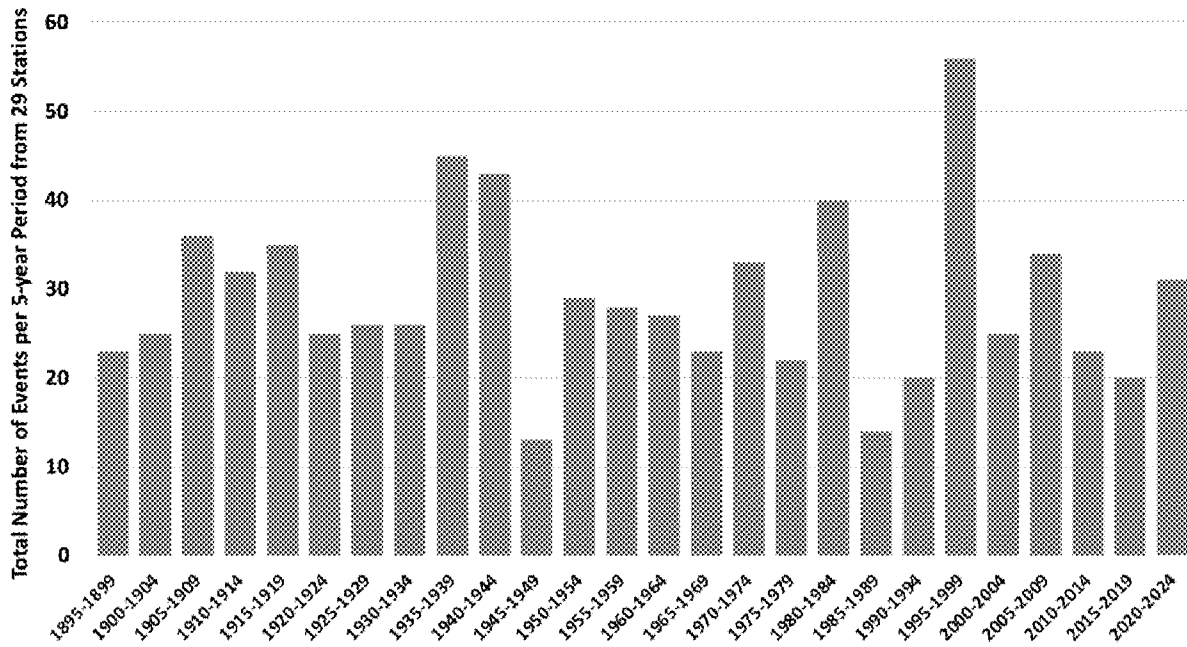


Figure 6.4.2. The time distribution by 5-year periods of the 26 heaviest (1-in-5 yr) occurrences for 29 stations on the Pacific coast.

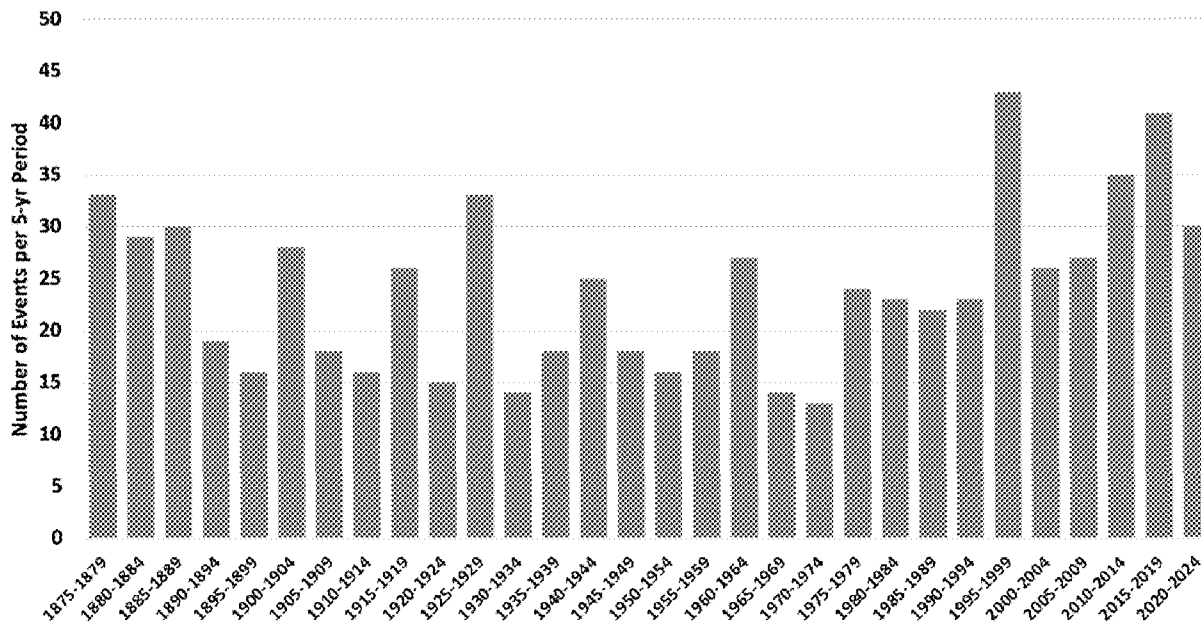


Figure 6.4.3. As in Fig. 6.4.2 but for the heaviest 30 (1-in-5yr) events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

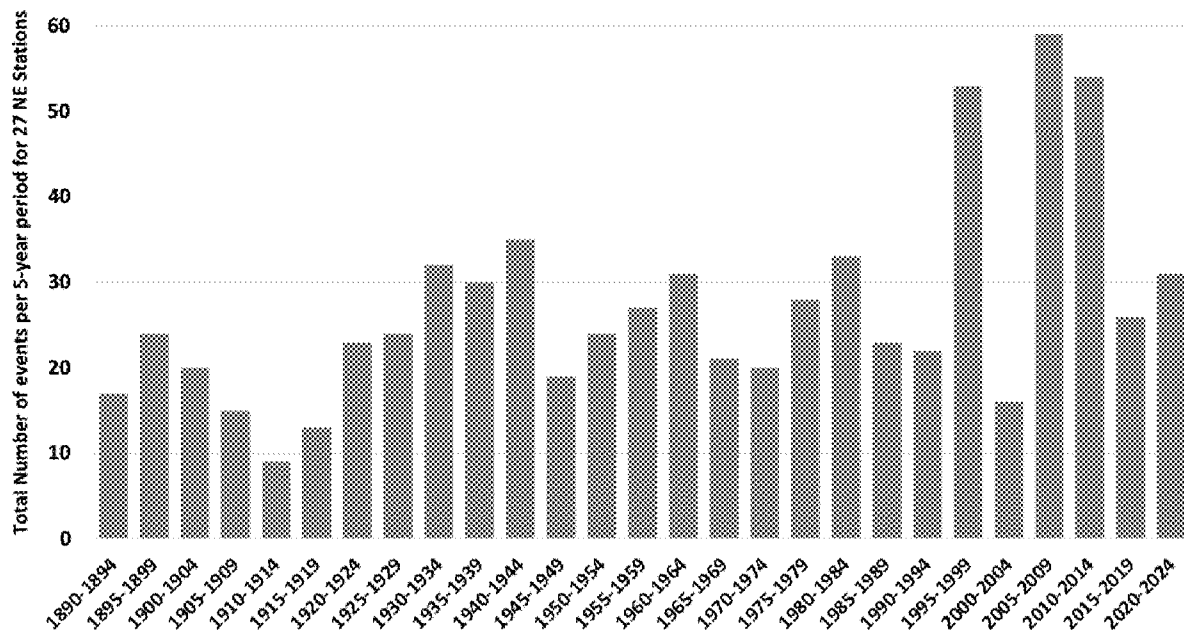


Figure 6.4.4. As in Fig. 6.4.2 but for the heaviest 27 (1-in-5yr) 3-day precipitation events for 27 Northeast stations from NY to ME, including Montreal.

Northeast heavy rainfall events

- The trend in average precipitation is positive and statistically significant in 12 of 27 locations and also in the regional average.
- The trend in rainfall variance is positive and significant in Portland ME, Albany NY, Buffalo NY and Eastport ME but insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Portland ME, Gardiner ME and Eastport ME but insignificant elsewhere.
- When averaged over all stations in the region, there is no statistically significant trend in either the precipitation variance or maximum

Fig. 6.4.4 is analogous to Figure 6.4.2 for the last 135 years in 27 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest temporal variations in time. In this region, 77 percent of events occur during June to October and are dominated by incursions of hurricanes, tropical storms, or tropical storms that transition to extratropical systems. According to NCA4 and NCA5 this region experienced the largest increases in extreme events, so it merits a closer examination.

There is a noticeable clustering of extreme events from 1995 to 2014. Howarth *et al.* (2019) examined a similar region as in Fig. 6.4.4 that includes PA and NJ and reported significant differences in various precipitation extremes between two 18-year periods, 1979-96 and 1997-2014. That included a 317 percent increase in 24-hr events exceeding 6 inches, while we find a 58 percent increase over the same years. However, Figure 6.4.4 shows that frequency drops sharply after 2014, returning to the long-term average in the subsequent 5-year intervals, again illustrating the perils of drawing conclusions from short-term trends in highly variable metrics.

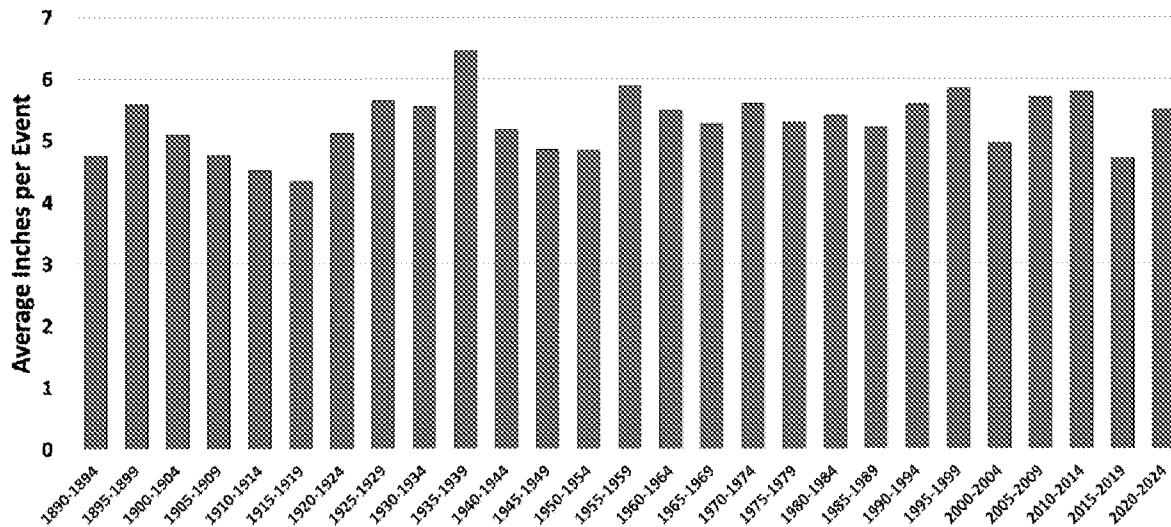


Figure 6.4.5. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

The high percentage increase in the Howarth *et al.* sample is associated with small numbers at relatively few locations: there were only 6 in the first period and 25 in the second across 58 stations. Most of the stations did not record such an event. If there is a region-wide increase in heavy events, it should be seen in the average across all stations. Figure 6.4.5 shows the average precipitation in the 1-in-5 yr events across the NE. The trend is only +0.04 inches/decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 6.4.4 and 6.4.5 thus suggest that though there was a surge in the number of events at a few locations during the 1995 to 2014 interval, there was no regional pattern and the change did not persist beyond 2014.

Jong *et al.* (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded “The autumn extreme precipitation trend over the Northeast U.S. is primarily attributed to tropical cyclone-related events since the 1990s.” The question then becomes: “Was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs?” Jong *et al.* examined CMIP-6 model output which suggests that there will be fewer such systems in the 21st century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 6.4.5 where the amount-per-event has remained steady over the 135-year period.

There is some evidence to indicate the heaviest rainfall events might be redistributed due to the impact of urban infrastructure on the local weather (e.g., Pielke Sr. *et al.* 2011, Zhang *et al.* 2018, Yang *et al.* 2024). Yang *et al.* state “Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with dispersed development.” While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 6.4.5.

In summary, some U.S. regions show short-duration increases in extreme precipitation events, consistent with natural variability. But analysis of long term, nationwide historical records that considers the autocorrelation properties of precipitation data does not support the claim that extreme short-duration rainfall events are becoming more frequent or intense.

6.5 Tornadoes

AR6 assesses tornado trends in the U.S. as follows:

[O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

The monitoring of weak tornadoes has changed over time. The growth of rural populations and the increasing ability to take video with hand-held devices has led to more frequent reports of weak tornadoes that produce minimal damage. In contrast, strong to violent tornadoes have been observed more consistently over time. Note that tornado strength is measured by the damage it produces, not by the visual appearance of the funnel. Limited real-time observational capabilities in earlier decades did not prevent identification because strong to violent tornadoes leave much more damage which will be assessed later even if the tornado itself was not observed. Since statistics began in 1950, there has been a substantial decrease (by about 50%) in the number of strong to violent tornadoes as shown in Fig. 6.5.1a.

To summarize, there is a noticeable downward trend in the number of severe tornadoes in the U.S. since 1950. After 1990 the number of weak tornadoes in the U.S. has remained roughly constant; data before that are incomplete due to limited monitoring.

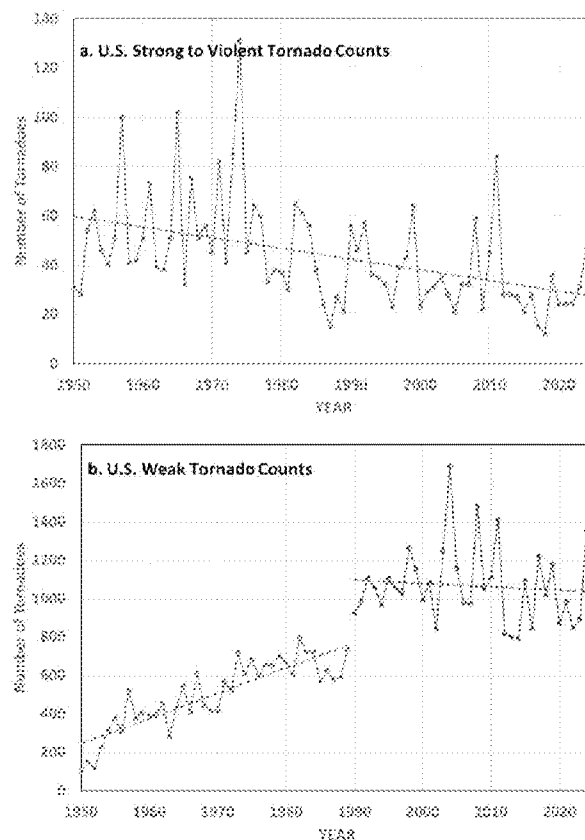


Figure 6.5.1. Annual U.S. tornado counts for (a) strong to violent tornadoes (EF3 to EF5), and (b) weak tornadoes (EF0 to EF2). Based upon NOAA Storms

Prediction Center data, available at https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv

6.6 Flooding

Changes in floods were assessed as follows:

AR6: The SREX assessed *low confidence* for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report. The SR15 found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. . . [H]ydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales. (Chapter 11.5)

AR6: [T]he seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). Confidence about peak flow trends over past decades on the global scale is *low*. (Chapter 11.5)

NCA4: Trends in extreme high values of streamflow are **mixed** across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude **but does not provide robust evidence** that these trends are attributable to human influences (pp. 240-241)

The absence of detectable US-wide trends in flooding is consistent with the findings in Section 6.4 of absence of coherent changes in extreme precipitation.

6.7 Droughts

Assessments of drought trends were as follows.

AR6: Few AR6 regions show observed increases in meteorological drought (Section 11.9, p. 1575),

AR6: Increasing trends in agricultural and ecological droughts have been observed on all continents (*medium confidence*), but decreases only in one AR6 region (*medium confidence*). Increasing trends in hydrological droughts have been observed in a few AR6 regions. (Chapter 11 Summary)

NCA4: As a consequence of this increased precipitation, **drought statistics over the entire CONUS have declined**. (p. 233)

NCA4: Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the **1930s remains the benchmark** drought and extreme heat event in the historical record (very high confidence). (p.231)

SREX: From a paleoclimate perspective, **recent droughts are not unprecedented**, with severe ‘megadroughts’ reported in the paleoclimatic record for Europe, North America, and Australia. (p. 170)

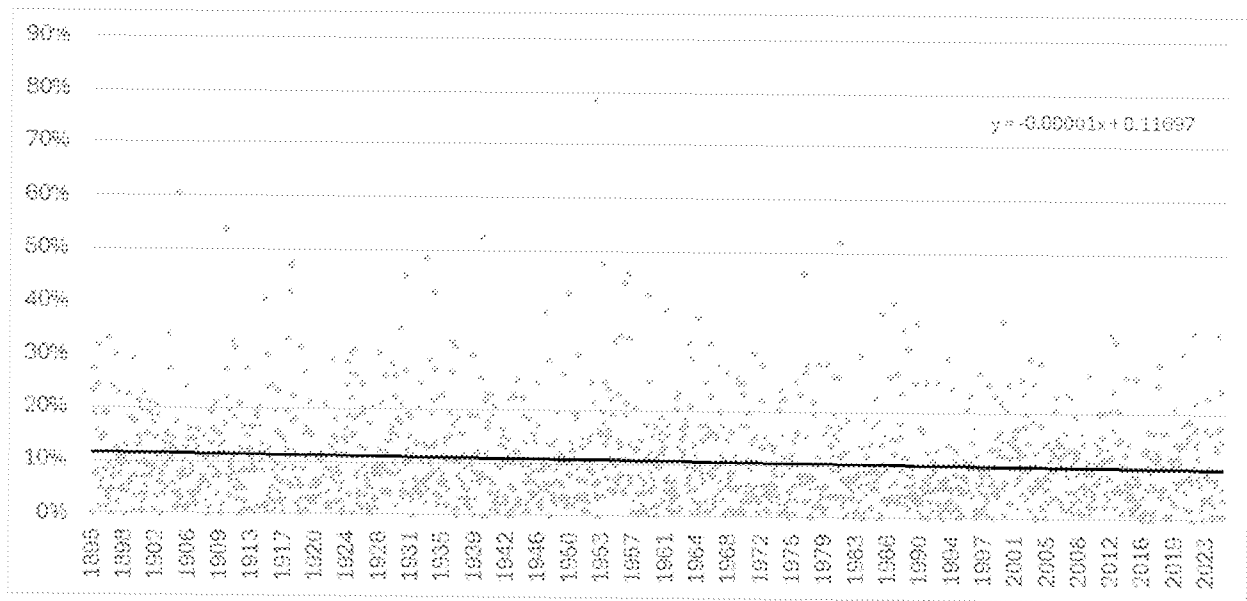


Figure 6.7.1: Monthly percent of US classified as “Very Dry” 1895—2025. Data source: NOAA <https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0> least squares trendline added.

As shown in Figure 6.7.1, U.S. long-term data shows an insignificantly declining trend in extreme dryness (-0.001 percent per year)

Kogan *et al.* (2020) examines a 38-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: “it is possible to state firmly that global and main grain countries’ drought area and intensity trends have not been following global climate warming since 1980’s.”

In summary there is no evidence of increasing drought frequency or intensity in the U.S. or globally over recent decades.

6.8 Wildfires

The IPCC has not provided an assessment of wildfires. As shown in Figure 6.8.1, global wildfire activity as measured by European Space Agency shows a downward trend in the 21st century.

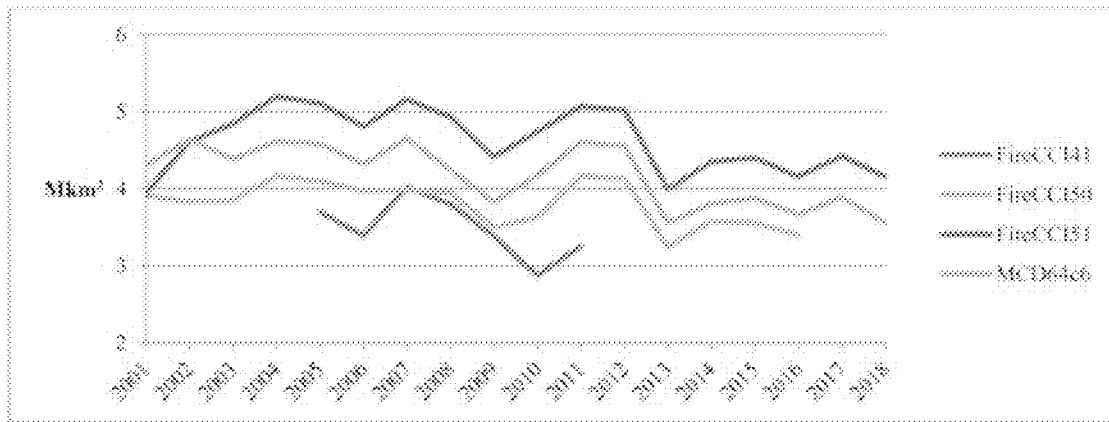


Figure 6.8.1: Global wildfire area 2001-2018. Source: From Lizundia-Loiola *et al.* (2021) Figure 12. The different coloured lines represent data products derived from different satellites and algorithms

Global data show that wildfire coverage is constant or declining on every continent (Samborska and Ritchie, 2024).

Active fire suppression since 1900 makes it difficult to establish a natural baseline for wildfire activity in the U.S. Paleoclimatic evidence indicates that past activity was much higher than today. Marlon *et al.* (2012) used sedimentary charcoal layers to reconstruct fire history of western U.S. for the past 1400 years and also fit a model to predict fire activity as a function of climatic conditions. Their results are summarized in Figure 6.8.2 below (from Figure 2 in their paper). There has been a growing wildfire deficit over the 20th century. In other words, however much fire was observed in the 20th century, it was less than what would have been observed in previous centuries based on the climatic conditions. Parks *et al.* (2025) likewise find that despite the recent increase in wildfire burn area in North America, a significant wildfire deficit remains relative to historical wildfire regimes.

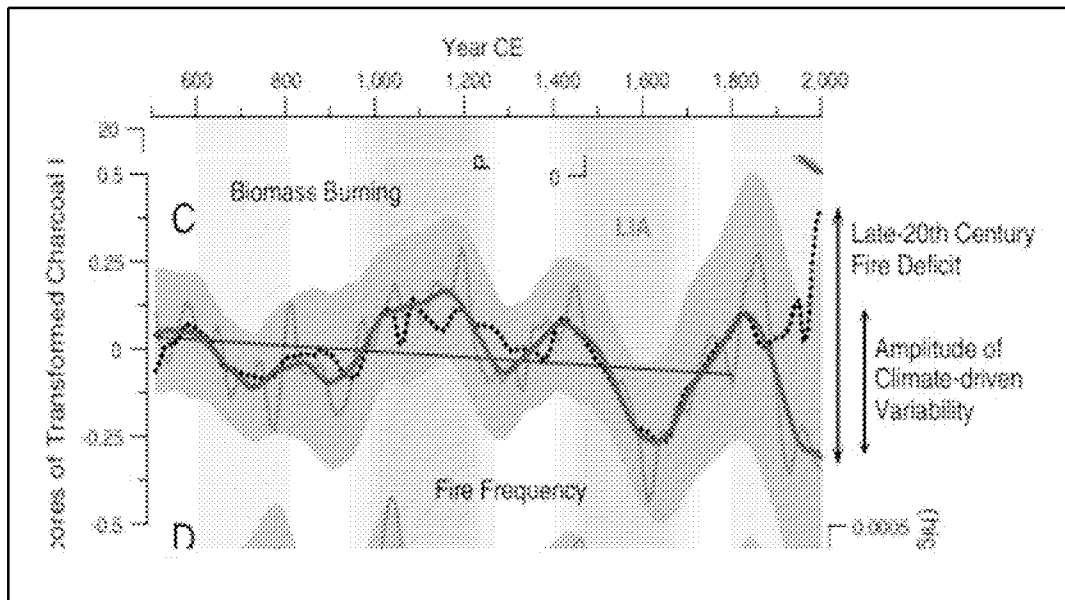


Figure 6.8.2 Fire frequency and fire deficit in the US. The red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based on climatic conditions. Source: Marlon *et al.* (2012) Figure 2.

U.S. data from the National Interagency Fire Centre (NIFC) from 1926 to 2023 are shown in Figure 6.8.3. The NIFC has removed the pre-1960 data from its current website on the grounds that measurement methods changed after 1960 making the comparison unreliable. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

Forest fires have always been a part of nature, and they can certainly create conditions that are inhospitable in the short term for all life, including humans. Science has confirmed the overall benefit and necessity of forest fires. While recent high-profile fires and seasons serve as a reminder of the potential destructive impact, the highest profile U.S. forest fire remains the 1910 Big Blowup fire in the U.S. west, which destroyed over three million acres and eliminated entire towns like Taft, MT (Apple, 2020). The 1910 fire reshaped the U.S. Forest Service (National Forest Foundation 2022) leading to a focus on fire suppression with a primary goal of defeating all forest fires (Forest History Society, 2022). This led to the “10 am rule” in 1935 requiring that all fires spotted on any day had to be controlled by 10 am the following day (National Forest Foundation, 2022).

While defeating all fires seemed a noble goal, questions began to arise as to whether this behavior “followed the science” (U.S. Forest Service, 2022). Over time the U.S. Forest Service has begun to rethink its goals, recognizing that new approaches such as prescribed burns, fuel elimination, and controlled wildfires are more appropriate (Sommer, 2016). Recent research is validating this approach and recognizing that more frequent smaller fires likely result in healthier forests, water ecosystems and biodiversity (Stephens *et al.*, 2021).

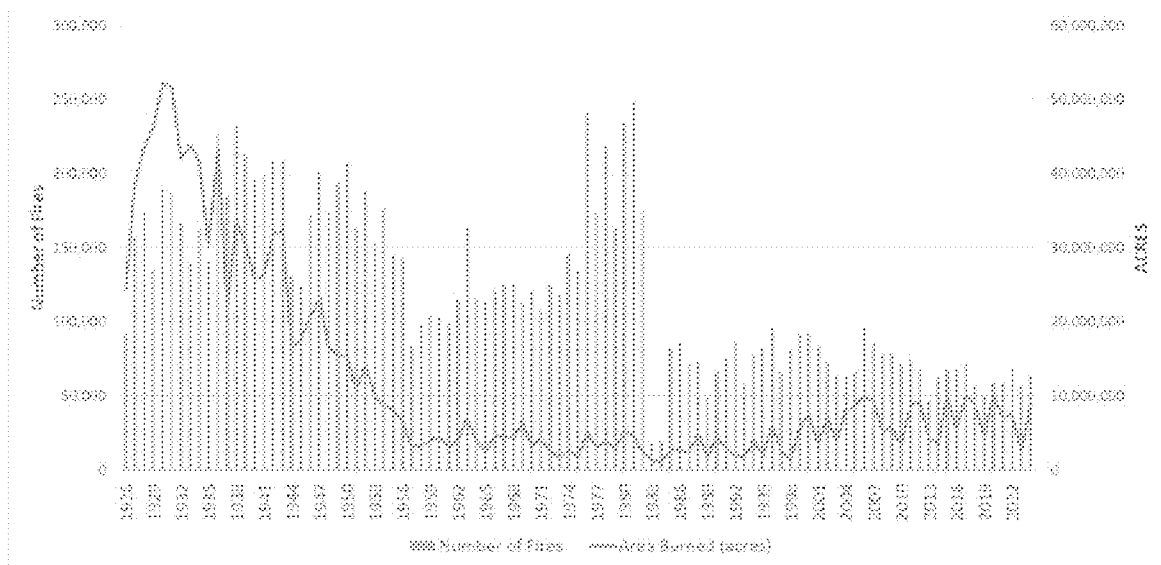


Figure 6.8.3: U.S. wildfires 1926 to 2023. Source: Post-2018: National InterAgency Fire Center data <https://www.nifc.gov/fire-information/statistics/wildfires>. Pre-2017 webarchive.org (n.d.).

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7 CHANGES IN SEA LEVEL

Chapter Summary

Since 1900, global average sea level has risen by about 8 inches. Sea level change along U.S. coasts is highly variable, associated with local variations in processes that contribute to sinking and also with ocean circulation patterns. The largest sea level increases along U.S. coasts are Galveston, New Orleans, and the Chesapeake Bay regions - each of these locations is associated with substantial local land sinking (subsidence) unrelated to climate change.

Extreme projections of global sea level rise are associated with an implausible extreme emissions scenario and inclusion of poorly understood processes associated with hypothetical ice sheet instabilities. In evaluating the IPCC AR6 projections to 2050 (with reference to the baseline period 1995-2014), almost half of the interval has elapsed by 2025, with sea level rising at a lower rate than predicted. U.S. tide gauge measurements reveal no obvious acceleration beyond the historical average rate of sea level rise.

7.1 Global sea level rise

Global sea level rise is arguably the most important climate impact driver that is unambiguously associated with increasing temperatures. At the global level, warming raises sea level through thermal expansion of sea water and through melting of glaciers and ice sheets. Variations in land water storage are another important factor. At the regional scale, sea level change is influenced by large-scale ocean circulation patterns, and geologic processes and deformation from the redistribution of ice and water. Locally, vertical land motion from geologic processes, ground water withdrawal, and fossil fuel extraction are also important.

The IPCC AR6 estimates that global mean sea level increased by 7.9 (5.9–9.8) inches between 1901 and 2018, with the rate of sea level rise accelerating in recent decades. At the ocean basin scale, sea levels have risen fastest in the Western Pacific and slowest in the Eastern Pacific over the period 1993–2018 (Fox-Kemper *et al.*, 2021). The rate of global sea level rise is estimated to be 0.12 inches/year, about the height of two stacked pennies (NASA, 2020).

The observing systems for global sea level rise have advanced significantly in the satellite era, particularly with the advent of satellite altimeters in 1993. Local tide gauges have provided useful data for the past century, and even longer for a few locations. Following the end of the Little Ice Age in the mid-nineteenth century, tide gauges show that the global mean sea level began rising during the period 1820–1860, well before most anthropogenic greenhouse gas emissions.

7.2 U.S. sea level rise

Observed and predicted rates of mean global sea level rise might have little scientific relevance for specific locations, owing to local processes (NOAA, 2025). Figure 7.1 shows that in Canada and Alaska (and also northern Washington), sea level is decreasing, owing to uplift from glacial rebound. Most of the Pacific coast tide gauges show low rates of sea level rise, while largest U.S. rates are on the Gulf coast (Louisiana and Texas) and in the mid-Atlantic states (Chesapeake Bay region).

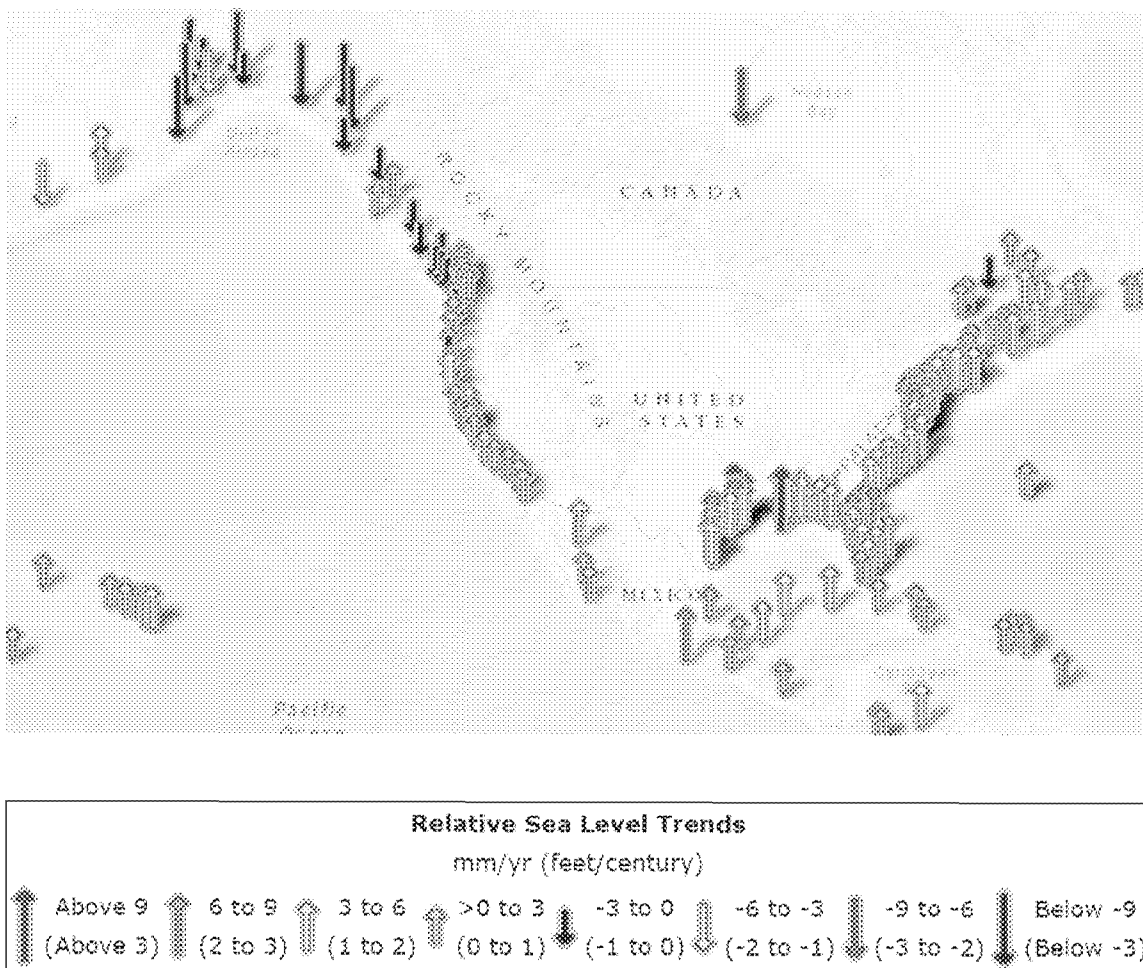


Figure 7.1. Map of rates of relative sea level rise along the U.S. coast (NOAA, <https://tidesandcurrents.noaa.gov/sltrends/>). For reference, 3 mm = 0.12 in.

Measurements of relative sea level rise from tide gauges conflate the climatologically relevant increase in the volume of seawater with local vertical land motion. The latter, which varies from place to place, is best measured using a Global Positioning System (GPS) station located near the tide gauge. It is driven by a range of processes that can be comparable to the climate signal and can locally exacerbate (subsidence/sinking) or mitigate (uplift) the risk of sea level rise (Wöppelmann and Marcos, 2016). Human activities triggering subsidence are often significant. They include soil drainage (*e.g.* for urban development) and subsurface extraction of groundwater or hydrocarbons.

Table 7.1 shows absolute sea-level rise (ASLR) for selected locations, determined from the sum of uncorrected sea-level rise as estimated from tide gauge time series (RSLR) (NOAA, 2025) and the vertical land motion (VLM) measurements (NAS, 2012; Letetrel *et al.*, 2015; Karegar *et al.*, 2016). The absolute sea level rise for each of these locations is significantly smaller than the measured relative sea level rise owing to local subsidence. More than half of the measured relative sea level rise is attributed to land sinking for these locations: San Francisco, Galveston, Grand Isle. For reference, the global average rate of absolute sea level rise is estimated to be 0.12 inches/year.

Location	RSLR	VLM	ASLR
San Francisco, CA	+0.08	-0.06	+0.02
Galveston, TX	+0.26	-0.19	+0.07
Grand Isle, LA	+0.36	-0.28	+0.08
St Petersburg, FL	+0.12	-0.02	+0.10
New York City, NY	+0.11	-0.05	+0.06

Table 7.1 Absolute sea level rise (inches/year) consisting of Relative Sea Level Rise (RSLR) plus Vertical Land Motion (VLM)

San Francisco Bay

Over the past 100 years, relative sea level in the San Francisco Bay area has risen by 7.8 inches, at an average rate of 0.08 inches/year (Figure 7.2). As shown in Table 7.1, San Francisco's vertical land motion is -0.06 inches/year (sinking), producing a recent absolute rate of +0.02 inches/year. Portions of Treasure Island, San Francisco International Airport, and Foster City are sinking as fast as 0.4 inches/year (Shirzaei and Bürgmann, 2018). Problems in the San Francisco Bay area, including threats to the airport, are caused primarily by soil compaction in landfill zones that were formerly wetlands, not by the slow creep of global sea level rise.

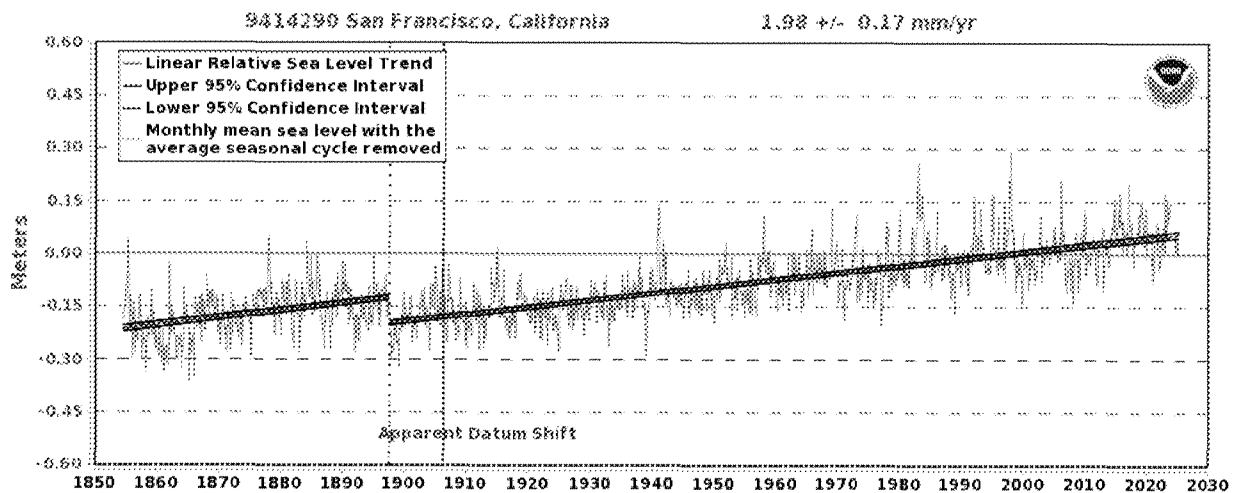


Figure 7.2. Tide gauge measurements at San Francisco, California, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290 (downloaded 4/22/25).

Galveston - Houston

Long-term tide measurements at Galveston Pier 21 show sea level rise of 2.18 feet in the past century, or a rate of 0.26 inches/year (Figure 7.3). Vertical land motion (subsidence) at Galveston is estimated at -0.19 inches/year, yielding an absolute rate of rise of +0.07 inches/year (Table 7.1). The U.S. Geologic Survey found that most of the land-surface subsidence in the Houston-Galveston region is a direct result of groundwater withdrawals (Kasmarek and Ramage 2017), which caused compaction of the aquifer sediments, mostly in the fine-grained silt and clay layers. By 1979, as much as 10 feet of subsidence had occurred in Houston.

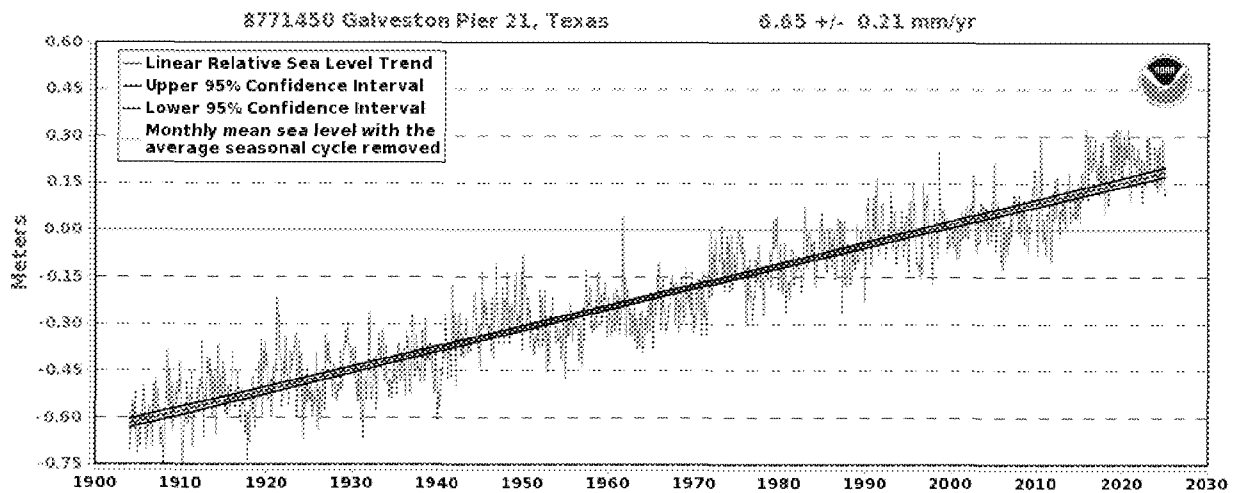


Figure 7.3. Tide gauge measurements Galveston Pier, TX, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8771450 (downloaded 4/22/2025).

New Orleans and the Mississippi delta

Long-term tide gauge measurements at Grand Isle, Louisiana, show that sea level has risen by slightly more than 3 feet over the last 100 years at an average rate of 0.36 inches/year (Figure 7.4). Vertical land motion (subsidence) is estimated -0.28 inches/year. Table 7.1 gives the absolute sea level rise as +0.08 inches/year.

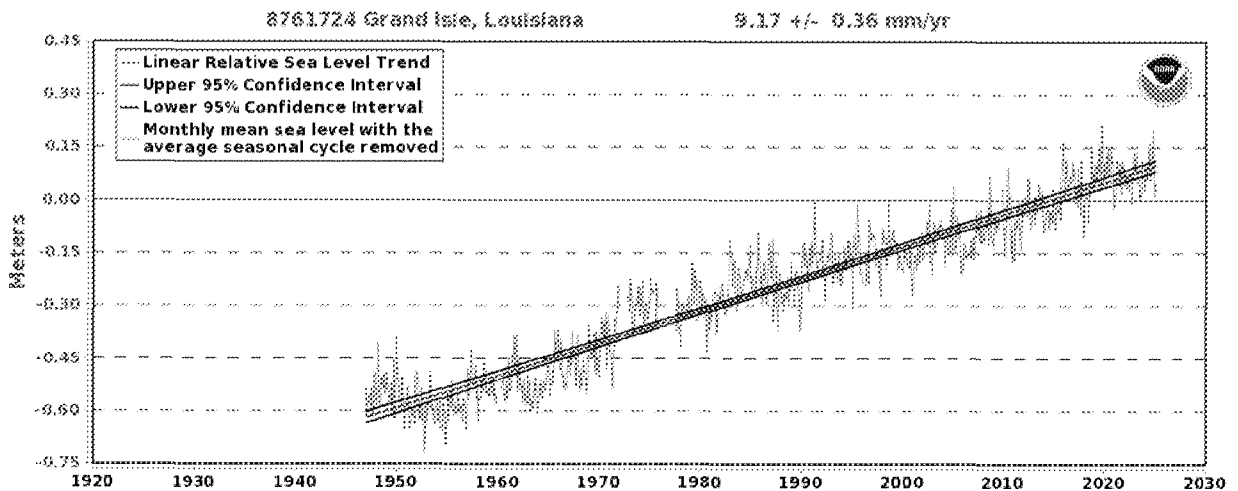


Figure 7.4. Tide gauge measurements at Grand Isle, LA, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8761724 (downloaded 4/22/25).

The issues of sea level rise and land loss in the Mississippi Delta region are complex, with geological subsidence and the decline in sediment transported by the Mississippi River being the dominant drivers. The construction of dams in the basin since the 1950s has decreased the Mississippi’s suspended sediment load by ~50 percent (Maloney 2018). A new subsidence map of coastal Louisiana finds the coastal region to be sinking at about one third of an inch per year (Neinhuis *et al.* 2017), associated with groundwater and resource withdrawal. As the city’s elevation averages one to two feet *below* sea level, sea level rise from anthropogenic warming is hardly the dominant driver of New Orleans’ problems.

New York City

New York City is particularly vulnerable to the effects of sea level rise because it is built primarily on islands and has 520 miles of coastline. Measurements by a tide gauge at the southern tip of Manhattan (The Battery) show that relative sea level has risen over 11 inches over the past century, at an average rate of 0.11 inches/year (Figure 7.5). But vertical land motion in the New York City area is -0.05 inches/year (roughly 5 inches per century), so that the absolute rate of sea level rise at The Battery is 0.06 inches/year, or about 55 percent of the measured relative sea level rise.

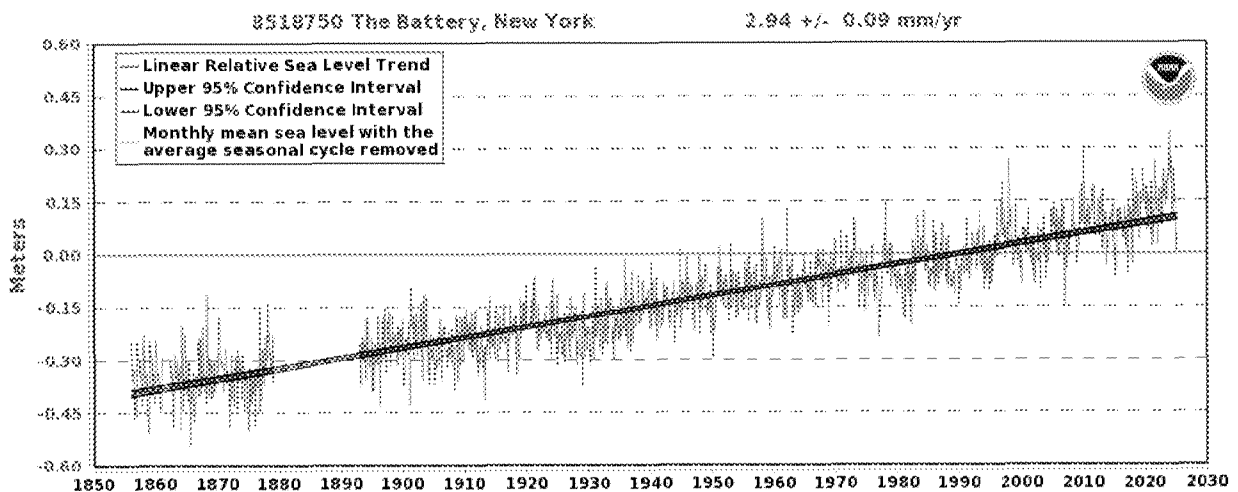


Figure 7.5. Tide gauge measurements at The Battery, New York, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750 (downloaded 4/22/25).

7.3 Projected sea level rise

The concern over sea level rise is not about the roughly eight inches of global rise since 1900. Rather, it is about projections of *accelerated* rise based upon simulations of a warming climate through the 21st century.

AR6 finds *high agreement* across published global mean sea level projections for 2050 with little sensitivity to emissions scenarios. Considering only projections incorporating ice-sheet processes in whose quantification there is at least *medium confidence*, the global sea level projections for 2050, across all emissions scenarios, fall between 3.94 and 15.75 inches (5th–95th percentile *very likely* range) relative to the 1995–2014 baseline period (Fox-Kemper *et al.*, 2021).

Conversely, AR6 states there is *low agreement* across published global mean sea level projections for 2100, particularly for higher emissions scenarios. Considering only projections representing ice sheet processes in whose quantification there is at least *medium confidence*, the AR6 global mean sea level projections for 2100 lie between 7.87 and 39.37 inches (5th–95th percentile *very likely* range) under the medium emissions scenario SSP2–4.5 (Fox-Kemper *et al.*, 2021). There is deep uncertainty surrounding projections of sea level rise to 2100 owing to uncertainties in ice sheet instabilities, particularly for the higher emissions scenarios.

In February 2022, NOAA issued its projections of sea level rise for various sites along the U.S. coast (Sweet *et al.*, 2022). They claim that by 2050, the sea will have risen one foot at The Battery in Manhattan (relative to 2020). A one-foot rise in thirty years would be more than twice the current rate and about three times the average rate over the past century. In that historical context, NOAA’s projection is remarkable—as shown in Figure 7.6, it would require a dramatic acceleration beyond anything observed since the early 20th century. But even more noteworthy is that Sweet *et al.* (2022) say this rise is “locked in”—it will happen no matter what future emissions are. We should know in a decade or so whether that prediction has legs.

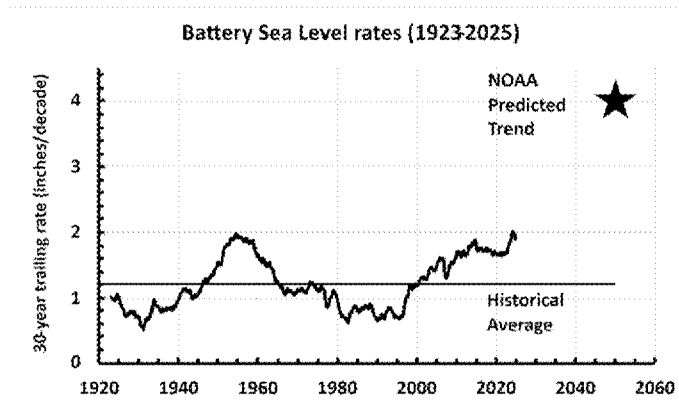


Figure 7.6 Rate of sea level rise at the Battery in Manhattan. Shown is the historical thirty-year trailing trend, together with the allegedly “locked in” NOAA predicted trend for 2050. Historical data: NOAA Tides and Current.

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8 UNCERTAINTIES IN CLIMATE CHANGE ATTRIBUTION

Chapter summary

“Attribution” refers to identifying the cause of some aspect of climate change, specifically with reference to anthropogenic activity. There is an ongoing scientific debate around attribution methods, particularly regarding extreme weather events. Attribution is made difficult by high natural variability, the relatively small expected anthropogenic signal, lack of high-quality data, and reliance on deficient climate models. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.

Substantive criticism of the main IPCC assessments of the role of CO₂ in recent warming focus on inadequate assessment of natural climate variability, uncertainties in measurement of solar variability and in aerosol forcing, and problems in the statistical methods used for attribution.

The IPCC does not make attribution claims for most climate impact drivers related to extreme events. Statements related to statistics of global extremes (*e.g.* event probability or return times, magnitude and frequency) are not generally considered accurate owing to data limitations and are made with low confidence. Attribution of individual extreme weather events is challenging due to their rarity. Conflicting claims about the causes of the 2021 Western North America Heatwave illustrate the perils of hasty attribution claims about individual extreme events.

8.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) distinguishes between detection of climate change and attribution of its cause. As defined by the AR6 WGI Glossary (IPCC, 2025):

Detection: Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%.

Attribution: Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence.

Both detection and attribution rely on statistical analysis. Detection focuses on whether changes are significant enough to stand out from random variation regardless of cause. Attribution involves comparison of observed events to model-generated counterfactuals. Since experimentation on the climate is not possible, attribution requires statistical inference to assess how much human activities (such as GHG emissions) versus natural factors (like volcanic eruptions) contribute to observed changes. Attribution methods assume all external and internal drivers of the system are known and represented.

There are ongoing scientific debates around attribution methods, especially those for attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. AR4 Working Group I (Hegerl *et al.*, 2007) explained it as follows:

‘Attribution’ of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is ‘consistent with the estimated responses to the given combination of anthropogenic and natural forcing’ and ‘not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings’ (IPCC, 2001)... The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

AR5 Working Group II (Cramer *et al.*, 2014) makes the following statement:

Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

8.2 Attribution methods

The IPCC employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key IPCC attribution methods.

Optimal Fingerprinting uses linear regression to explain variations in observed climate data as a weighted sum of climate model simulations run with and without anthropogenic forcings. The data used in the regression model is weighted to try to minimize the influence of random noise and the estimation method is chosen to account for climate model error.

Time Series Analysis exploits statistical differences between anthropogenic forcing and natural variability to see which dominates observed temperatures and also uses variations in the timing of changes to determine if causal dependence across data series can be inferred.

Process-Based Attribution focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification

Extreme Event Attribution assesses the role of human influence in the likelihood of occurrence or intensity of extreme weather events (*e.g.* heat waves or droughts). Methods include:

- Probabilistic Event Attribution uses large ensembles of climate model simulations to compare observed events to model-generated counterfactuals
- Storyline Approach examines the physical processes driving an event and evaluates how anthropogenic forcings might have modified those processes

8.3 Attribution of global warming

Attribution statements for global warming in the three most recent IPCC Assessment reports are:

AR4: **Most of the observed increase** in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations. (IPCC 2007)

AR5: It is *extremely likely* that **more than half of the observed increase** in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human-induced contribution to warming is similar to the observed warming over this period. (IPCC 2013)

AR6: The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that **well-mixed GHGs were the main driver** of tropospheric warming since 1979. (IPCC 2021)

The AR4 and AR5 attribution statements reference the warming since the mid-20th century, the period when greenhouse gas emissions began increasing rapidly. The words “most” and “more than half” are deliberately imprecise, potentially ranging from 51 to 99 percent of the warming – presumably this imprecision is to account for structural uncertainties such as natural internal variability. The confidence level increases from *very likely* to *extremely likely* from AR4 to AR5. The structure of the attribution statement in the AR6 is fundamentally different, referencing the warming to the period 1850–1900. The AR6 attribution statement is more precise numerically, but with a lower level of confidence at “likely” – AR6 attributes essentially all the warming to increases in greenhouse gases. The most confident statement from AR6 relates to the tropospheric warming since 1979, using the words “main driver” and “*very likely*.”

There are three areas of substantive criticism of the IPCC’s assessment of the causes of the recent warming: inadequate assessment of natural climate variability, inappropriate statistical methods, and substantial discrepancies between models and observations. The last is discussed in Chapter 5, while this chapter discusses the first two factors. All of these criticisms are relevant to the IPCC’s policy-informing attribution of the recent warming, which also underpins extreme event attribution

8.3.1 Natural climate variability

AR6 states that natural external drivers since 1850–1900 have changed global surface temperature by –0.1°C to +0.1°C, and internal variability has changed it by –0.2°C to +0.2°C – on average having essentially no net impact on the warming since 1850–1900. As discussed below, this minimal contribution of natural variability has been disputed by several publications that question the magnitudes of solar variability and internal variability from large-scale ocean circulations.

Solar variability

AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes over the period 1750–2011 was very small (0.05 W/m², Myrhe *et al.*, 2014). AR6 acknowledges substantially higher values and a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the twentieth century increased by 0.7–2.7 W/m², a range that includes both low and high variability TSI data

sets (Gulev, 2021). However, the recommended forcing dataset for the CMIP6 climate model simulations used in AR6 for attribution studies averages two data sets with low solar variability (Matthes, 2017).

While AR6 shows a substantially greater solar impact than does AR5, the overall impact of solar forcing on the climate was still assessed to be small compared to anthropogenic forcing. However, the impact of solar variations on the climate is uncertain and subject to substantial debate (Lockwood, 2012; Connolly *et al.*, 2021) - something that is not evident in the IPCC assessment reports.

The variations of TSI over time remains a challenging problem. Since 1978, there have been direct measurements of TSI from satellites. However, the data exhibits non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. There are several rival composite TSI datasets that disagree as to whether TSI increased or decreased during the period 1986–96 (the ACRIM gap; see Chapter 4). Further, the satellite record of TSI is used to calibrate proxy models that infer past solar variations from sunspots and cosmogenic isotope measurements (Velasco Herrera *et al.*, 2015).

There is substantial evidence for high solar activity in the second half of the 20th century (starting in 1959) and extending into the 1990's, before a decline in the early 21st century; this period is often termed the “Modern Maximum.” (Chatzistergos *et al.*, 2023; Solanki *et al.*, 2004; Usoskin *et al.*, 2007). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

This uncertainty causes some reconstructions of TSI from 1750 to have low variability (implying a very low impact of solar variations on global mean surface temperature) whereas datasets with high TSI variability can explain more than 70 percent of the temperature variability since preindustrial times (Scafetta, 2013; Stefani, 2021). The choice of TSI satellite record used in an analysis can therefore substantially influence how much climate change is attributed to human versus natural forcings.

There is growing evidence that other aspects of solar variability, which are referred to as solar indirect effects, either amplify TSI forcing or are independent of TSI forcing. Scafetta *et al.* (2023) suggests that ~80 percent of solar influence on climate might stem from non-TSI mechanisms. There are numerous candidate processes, including solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Such solar indirect effects are not included in climate models, although indirect methods of estimating their impacts suggest they are significant. However, claims of non-TSI mechanisms influencing climate are uncertain and debated.

Natural variability of large-scale ocean circulations

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns, including the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO). These circulations influence ocean heat uptake and heat distribution and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astronomical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability, most models have too little amplitude compared to observations at multi-decadal frequencies and phasing out-of-sync with the observed climate (Kravtsov *et al.* 2024). Averaging multiple simulations effectively averages out the internal variations, leaving only the forced climate variability (*e.g.* CO₂ forcing). With most of the modern warming beginning in the late 1970's, the recent 50-year warming is on the same time scale as the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the AR5 and AR6 reports:

AR5: Decadal variability in the Pacific, associated with the PDO or IPO [Interdecadal Pacific Oscillation], contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations.

AR6: Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (*high confidence*).

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: “The likely range of change due to internal variability is -0.2°C to $+0.2^{\circ}\text{C}$ (IPCC, 2021).” This implies a trough-to-peak change of 0.4°C . Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the past 50 years, when most of the recent warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual ensemble simulating a different phasing. Once the simulations of the ensemble members and different models are averaged, the natural internal variability contribution is averaged out owing to differences in phasing, effectively cancelling the role of natural internal variability in the attribution process.

The time series of global surface temperature anomalies since 1850 (Figure 8.1) shows irregular variations of significant amplitude against the background of an overall warming trend and, after 1976, a pronounced difference in trends between the Northern Hemisphere and the Southern Hemisphere. The period between 1905-1945 shows a strong trend of warming. The following 30 years from 1945-1976 showed slightly declining temperatures. The most recent warming period started in 1977.

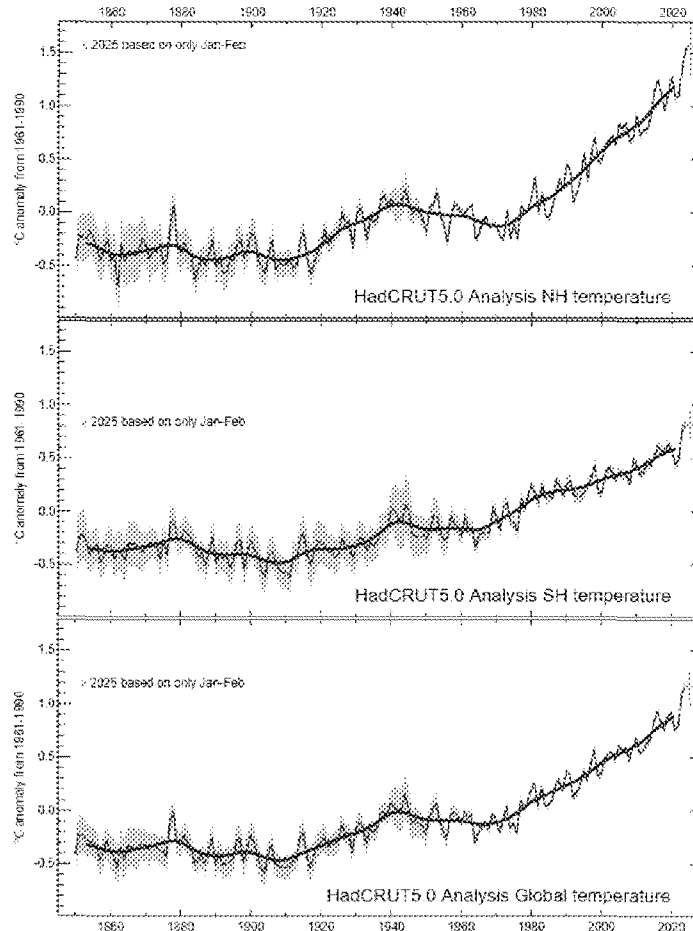


Figure 8.1 Global average surface temperature anomalies 1850—2025. Top: Northern hemisphere. Middle: Southern hemisphere. Bottom: Global average. Source: UK Hadley Centre <https://crudata.uea.ac.uk/cru/data/temperature/HadCRUT5.0Analysis.pdf>

The causes of the early 20th century warming are discussed by Hegerl *et al.* (2017; 2019). The atmospheric CO₂ concentration increased from 298 ppm in 1905 to 310 ppm in 1941, implying that CO₂ had little impact. Volcanic activity during this period was very low, and solar forcing is uncertain. Yet Hegerl *et al.* (2017) somehow inferred that 40-54 percent of this warming could be attributed to external forcing, with the rest associated with internal variability. Bronniman *et al.* (2024) focused on the causes of the cooling in the first decade of the 20th century in the Southern Hemisphere. They found that the cooling was related to a La-Niña-like pattern in the Pacific, a cold tropical and subtropical South Atlantic, a cold extratropical South Pacific, and cool southern midlatitude land areas. The Southern Annular Mode was positive, with a strengthened Amundsen–Bellingshausen seas low, although the spread of the data products is considerable.

The warming in the 1930's and subsequent cooling during mid-century was particularly pronounced in the Arctic. Bokuchava and Semenov (2021) find that these variations were most likely caused by a combined effect of long-term natural climate variations in the North Atlantic and North Pacific with a contribution of the natural radiative forcing related to the reduced volcanic activity and variations of solar activity, as well as growing greenhouse gases concentrations. Tokinaga *et al.* (2017) showed that the combined effect of internally generated Pacific and Atlantic interdecadal variability intensified Arctic

warming in the early 20th century. The synchronized Pacific-Atlantic warming drastically alters planetary-scale circulations over the Northern Hemisphere; these same circulation patterns have a global influence.

The cooling period between 1945 and 1976 has been referred to as the “grand hiatus.” Numerous causes have been hypothesized: natural internal variability from fluctuations associated with the Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation; cooling from increased emissions of aerosols from industrial activities; increased heat uptake in the Atlantic, Southern and Equatorial Pacific Oceans. Thompson *et al.* (2010) find that the hemispheric differences in temperature trends in the middle of the twentieth century stem largely from a rapid drop in Northern Hemisphere sea surface temperatures of about 0.3 °C between about 1968 and 1972.

The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947–1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns, including the frequencies of El Niño and La Niña events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming. When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, 40 percent or more of the warming in the second half of the 20th century is attributed to natural internal variability (McLean *et al.*, 2009; Tung and Zhou, 2013; Chylek *et al.*, 2016; Scafetta, 2021).

8.3.2 Optimal fingerprinting

Optimal fingerprinting is a statistical technique introduced by Allen and Tett (1999) that compares observed climate data to climate model simulations to identify patterns (or “fingerprints”) associated with human or natural forcing. It involves taking a vector of observed climate changes, such as warming rates in locations around the world, and decomposing them into a weighted sum of “signals”, which are analogues to the observations generated by climate models with different types of forcings. The weights are chosen using a regression method called Total Least Squares (TLS). The analysis commonly uses just two signals, one generated by models using only anthropogenic forcings and one using only natural forcings. If the estimated weighting coefficient attached to a signal is significantly different from zero, then that signal is said to be “detected”. If it is close to 1.0, then the model generating the signal is said to be consistent with observations. If it is less than 1.0, then the model signal for that forcing is too strong and needs to be scaled down, and vice-versa. Both the observed data and the signals are weighted using a model-generated estimate of patterns of randomness in the climate system so as, in principle, to put maximum weight on regions where natural variability is minimized.

Optimal fingerprinting is the primary tool for attribution in the research literature. While it has been widely used and prominently featured by the IPCC since 2001, there is very little literature examining the statistical properties of the results it generates. One of its inherent weaknesses is that results depend on assumptions about the accuracy of climate models, especially regarding their representation of natural variability (IPCC AR5 Ch 10.2.3).

A series of papers by McKittrick (McKittrick 2021, 2022, 2023, 2025) has challenged the optimal fingerprinting method, arguing that it is inherently unreliable and that practices adopted from econometrics can provide more valid results. Statistical theory requires that for regression models to yield unbiased coefficients, a set of assumptions called the Gauss-Markov conditions must hold. McKittrick (2021) argued that the Allen and Tett (1999) methodology violates the Gauss-Markov conditions, leading to potentially biased and inconsistent fingerprinting coefficients, undermining the reliability of the method. Chen *et al.* (2023) confirmed this analysis, although they argued that the method could yield valid results under very stringent assumptions. McKittrick (2022) and (2023) raised a further concern that climate scientists—virtually alone among

scientific disciplines—have used TLS to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unstable unless some strong assumptions hold that in practice are unlikely to be true. Under conditions that easily arise in optimal fingerprinting, TLS estimates have a large positive bias. Thus, any study that used TLS for optimal fingerprinting without verifying its applicability in the specific data context has likely overstated the attribution.

McKittrick (2025) presented an empirical example comparing the results of conventional optimal fingerprinting against methods drawn from mainstream econometrics that are known to be valid for the specific application of signal detection. While the IPCC optimal fingerprinting method yields an anthropogenic signal coefficient close to 1.0 on a global temperature data set spanning 1900 to 2010, consistent estimation yields a coefficient around 0.4, which rises to about 0.65 on data spanning 1980 to 2010, implying the model response to greenhouse gases needs to be scaled down by about half to optimally match observations. The natural forcing signal coefficient, by contrast, is between 2.0 and 4.0, implying the climate model signals of natural forcing need to be scaled up two-to four-fold to match observed climate change. The fingerprinting coefficients estimated in McKittrick (2025), when used to scale the average sensitivity of the climate models used to generate the forcing signals in his data set, imply a Transient Climate Sensitivity of 1.4°C, which is consistent with the estimate by Lewis (2023) using a different estimation method and multiple independent data sets.

While these analyses do not falsify results of the IPCC optimal fingerprinting method, they do challenge the basis on which they were believed to be correct.

8.3.3 Time series methods

The IPCC (AR5 WGI 10.2.2) drew attention to alternative approaches of assessing causality that emerged from the time series econometrics literature. These have the advantage of not depending on assumptions about the accuracy of climate models, but the disadvantage that they depend on difficult-to-test assumptions about the data generating process underlying climate and forcing data. The methods, now referred to as climate econometrics, use the tools of unit root testing, Granger causality and cointegration analysis, all of which are familiar in economics and finance and which are slowly being adopted in climate science. Time series analysis methods hold out the possibility of determining whether anthropogenic or natural forcings are the primary drivers of climate change without requiring the use of climate models, although key questions remain unsettled (e.g. Dergiades *et al.*, 2016, Balcombe *et al.*, 2019, Dagsvik *et al.*, 2020, Razzak, 2022, Dagsvik and Moen, 2023).

“Granger causality” modeling is a tool for determining directions of influence in data series that move together. It is a statistical, not a physical, concept. If knowing the current value of one variable significantly improves the forecast accuracy of another variable, we can infer a causal connection exists; this is called Granger causality. The modeling tools, called vector autoregression, measure direct impulse-response patterns and feedbacks. An application to the well-known Vostok ice core data revealed an error in Al Gore’s documentary *An Inconvenient Truth*. Gore showed the data and drew attention to the coherence of temperature and CO₂ changes over a 440,000 year span, which he asserted was due to CO₂ driving temperature changes. But temperature changes can also affect atmospheric CO₂ levels. Davidson *et al.* (2015) examined the series and found that temperature Granger causes CO₂ but not the reverse. In other words on the time scales represented in the Vostok data, the coherence in the series is primarily due to the influence of temperature on CO₂ levels, not the feedback of CO₂ levels on temperature.

In summary, the primary statistical methods for attributing causation in climate data are optimal fingerprinting and time series analysis. Applications of the Allen and Tett (1999) optimal fingerprinting method dominate the attribution literature and have underpinned past IPCC conclusions, but results depend on the accuracy of climate models and the method has recently been criticized as inherently biased. Time

series methods do not depend on climate models but require assumptions of their own and have generated results that have thus far not converged on a consensus.

8.4 Declining planetary albedo and recent record warmth

A sharp recent increase in global average temperatures has raised the question of short-term drivers of climate. One such candidate is the fraction of absorbed solar radiation which has also increased abruptly in recent years. The question is whether the change is an internal feedback to warming caused by greenhouse gases, or whether something else increased the fraction of absorbed radiation which then caused the recent warming.

The planetary albedo is the fraction of incoming solar radiation that is reflected back into space rather than being absorbed by the planet. Highly reflective surfaces like cloud tops and snow and ice are most important in this regard. The Earth's albedo is approximately 30 percent, meaning almost a third of the sunlight that reaches Earth is directly reflected back to space. A lower albedo implies more solar energy is absorbed by the planet to be then re-radiated as heat. Hence, other things being equal, a decline in planetary albedo is associated with a warming of the Earth.

Arguably the most striking change in the Earth's climate system during the 21st century is a significant reduction in planetary albedo since 2015, which has coincided with at least two years of record global warmth. Figure 8.2 shows the planetary albedo variations since 2000, when there are good satellite observations. The 0.5 percent reduction in planetary albedo since 2015 corresponds to an increase of 1.7 W/m² in absorbed solar radiation averaged over the planet (Hansen and Karecha, 2025). For comparison, the IPCC estimate of forcing from the increase in atmospheric CO₂ compared to preindustrial times is approximately 2.2 W/m² (Figure 3.1.2).

Looking back prior to 2000 with less adequate data, Goessling *et al.* (2025) assessed that the planetary albedo was relatively low around the 1940's and 50's before rising industrial aerosol precursor emissions increased the albedo until the 1980's. The strongest planetary albedo excursions were high-albedo episodes caused by volcanic eruptions, such as after the Mount Pinatubo eruption in 1991. Although uncertain, the 2023 planetary albedo minimum might have been the lowest since at least 1940.

Changes in surface characteristics cannot explain this decrease in planetary albedo since 2015:

- Arctic sea ice extent has declined by about 5 percent since 1980 (https://nsidc.org/data/seaice_index/images/s_plot_hires.png), although following 2007 there has been a pause in the Arctic sea ice decline (England *et al.*, 2025)
- Regarding Antarctic sea ice, the IPCC AR6 concludes that “There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability.” (Summary for Policymakers, A.1.5)
- Northern hemispheric annual snow cover has been slowly declining since 1967, with barely significant trends. The data show the Northern Hemisphere has snowier winters, accompanied by more rapid melt in spring and summer, see <http://climate.rutgers.edu/snowcover/> and Section 5.6
- Global greening (Chapter 2) is contributing to the decrease in planetary albedo, as forests have a lower albedo than open lands or snow. However, there is some evidence that forests increase cloud cover (high reflectivity), which counteracts the direct albedo decrease associated with increasing forested area.

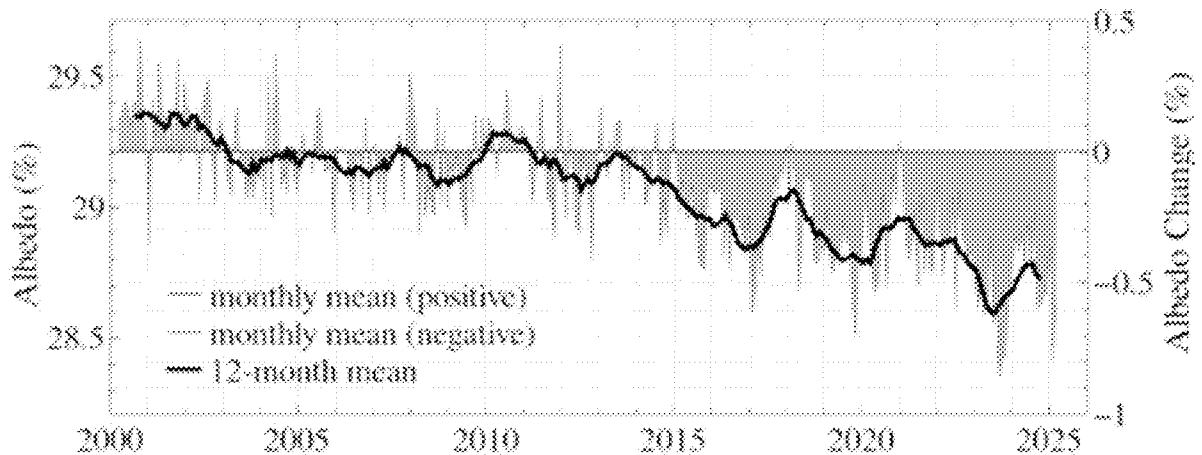


Figure 8.2. Earth's albedo (reflectivity, in percent), with seasonality removed. From Hansen and Karecha (2025)

Changes in surface reflectivity are contributing to a small, slow decline in planetary albedo. However, these changes cannot explain the sharp decline in planetary albedo beginning in 2015. Further, any changes in surface albedo are effectively damped by about a factor of three on average, primarily due to cloud masking (Loeb *et al.* 2019). Surface albedo changes have thus contributed only weakly to the recent planetary albedo decline, particularly when averaged annually and globally. This leaves the most likely explanation for the sharp albedo decline as changes in atmospheric aerosols and/or clouds.

Aerosols are small particles in the atmosphere that reflect sunlight and can interact with cloud processes to make the clouds more reflective. Aerosols have both natural origins (*e.g.* dust from soils, wildfires) as well as human origins from combustion (including fossil fuels). Regions that are greening and/or have an increase in rainfall might produce less dust. For anthropogenic aerosols, new ship fuel regulations aimed at reducing sulfur emissions were implemented in three phases, in 2010, 2015 and 2020. Sulfate particles reflect solar radiation. Cleaner air means less solar radiation is reflected, which contributes to surface warming. Indirect effects of sulfate aerosols include increasing the reflectivity of low-level clouds in the subtropics. There is controversy surrounding the importance of this change in sulfate emissions to the Earth's radiation balance (Hodnebrog *et al.*, 2024; Yuan *et al.*, 2024), but the restriction of this effect to major shipping routes suggests a small global impact (Schmidt, 2024).

Changes in clouds are the primary candidate to explain the decline in global albedo since 2015. Two recent papers (Loeb *et al.*, 2024; Goessling *et al.* 2024) have addressed recent variations in cloud properties. By considering satellite and reanalysis data, Loeb *et al.* found that decreases in low- and mid-level clouds since 2015 are the primary reason for decreasing planetary albedo in the Northern hemisphere, whereas in the Southern hemisphere the decrease in planetary albedo is primarily due to decreases in mid-level clouds across all latitude zones. Goessling *et al.* (2024) found that cloud anomalies were mainly due to reduced low-level clouds. Regions with coherent low-level cloud reductions over the past decade include the warm pool region around the Maritime Continent and the northern extratropical western Pacific, as well as large parts of the Atlantic and adjacent land regions. The reduction of global cloud cover identified in these analyses since 2015 is 1-2 percent.

The issue then becomes the cause of the change in cloud cover. Two explanations have been posited for the declining cloud cover over the past decade:

- Natural climate variability

- Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha, 2025)

It is not easy to justify a new positive low cloud feedback that began emerging in 2015. However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds:

- The 2014-2016 was one of the strongest El Niño events on record
- A cold anomaly beginning in 2015 in the subpolar gyre of the North Atlantic reflects a shift in the ocean circulation pattern associated with decadal variability in the Atlantic (Frajka-Williams *et al.*, 2017; Arthun *et al.* 2021).
- The Pacific Decadal Oscillation positive index peaked in 2016, then declined and has been in negative territory since late 2019
- Eruption of the submarine Hunga-Tonga volcano in 2022

Interannual cloud anomalies associated with the El Niño Southern Oscillation (ENSO) have a significant global signal and strong regional signals, especially over the tropical Indian and Pacific Oceans.

The Hunga Tonga eruption is remarkable in its coincidence with the exceptionally low value of planetary albedo in 2023. Goessling *et al.* (2024) found that the cloud perturbations in 2023 showed a different pattern from the overall pattern since 2015, with reduced cloud cover being most pronounced in the northern hemisphere and tropics. Regional reductions in cloud cover were most pronounced over the eastern Indian Ocean, over South America and extending over the eastern Pacific, as well as over northern North America, in the Southern Ocean around 60S, in the subtropical and eastern North Atlantic, and in parts of the North Pacific.

The Hunga Tonga eruption was unusual in that it injected large amounts of water vapor into the stratosphere in addition to sulfate particles. Early publications focused on the impacts to stratospheric circulations and the direct radiative impact. In 2025, papers are emerging that examine the indirect effects of Hunga Tonga on surface climate using ensemble simulations from earth system models (Bednarz *et al.*, 2025; Kuchar *et al.*, 2025). These papers found statistically significant impacts on regional climates that were driven by circulation changes from couplings between the stratosphere and troposphere. These papers indicate the complex interactions between volcanic activity and climate dynamics. More research is needed to untangle any impacts of the Hunga Tonga eruption on the planetary albedo.

In summary, the decline in planetary albedo and the concurrent decline in cloudiness have emphasized the importance of clouds and their variations to global climate variability and change. A change of 1- 2 percent in global cloud cover has a greater radiative impact on the climate than the direct radiative effect of doubling CO₂. While it is difficult to untangle causes of the recent trend, the competing explanations for the cause of the declining cloud cover have substantial implications for assessing the Equilibrium Climate Sensitivity and for the attribution of the recent warming. An additional 10 years of data should help clarify whether this is a strong positive cloud feedback associated with warming or a temporary fluctuation driven by natural variability

8.5 Attribution of climate impact drivers

The IPCC (Ranasinghe *et al.* 2021) defines “climate impact drivers” or CIDs as “physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems.” Hence CIDs are those features of the weather and climate system of primary interest in assessing the impacts of climate change since they potentially affect humans and the natural world. For instance, under the heading “Heat and Cold,” CIDs are identified as mean air temperature, extreme heat, cold spells and frost. The IPCC

also points out that CIDs are not necessarily harm-related: depending on the system in question they can be detrimental, neutral, beneficial or a combination.

The first columns Table 12.12 in Ranasinghe *et al.* (2021, p. 1856), reproduced here as Table 8.1, summarize the AR6 assessment of whether a signal of attributable anthropogenic influence has emerged across all major CIDs. One of the themes of this chapter is that attribution methods used by the IPCC tend to overstate the anthropogenic influence and understate the role of natural variability. Nonetheless a striking feature of that summary table is how few CIDs exhibit an anthropogenic signal sufficient to distinguish them from natural variability.

Out of the 33 weather impact categories listed, an anthropogenic signal is asserted with *high confidence* in only five, and with *medium confidence* in a further four. (Note that one of the CIDs is an increase in CO₂ levels, and since it is a tautology to attribute this to increased CO₂ levels this CID can be ignored.) For the rest the IPCC does not claim to have detected anthropogenic drivers. Of the five *high confidence assertions*, two are for changes in average temperatures (air and ocean) hence are not measures of extreme weather. Further, two of the four *medium confidence* assertions are related to ocean chemistry and thus are likewise not related to extreme weather. The IPCC does not assert a human influence on many non-temperature weather features such as wind, precipitation, flooding, or drought.

Other columns of IPCC Table 12.12 report on whether anthropogenic signals are expected to emerge this century under RCP8.5, the most extreme forcing scenario. We have omitted these columns for several reasons. First, because they refer to whether climate models project detectable signals in the observations, which is a very different question than our concern here: whether a signal has been detected in historical data. Second, as we discuss in Chapter 4, the RCP8.5 scenario is a misleading and implausible high-end storyline, it is not a “base case” or business-as-usual projection. Third, the ensemble of detailed models is acknowledged (Palmer and Stevens 2019) to be “not fit for purpose” in describing regional changes and “unable to represent future conditions at the degree of spatial, temporal, and probabilistic precision with which projections are often provided.” (Nissan et al, 2019). Even with these caveats, we note that the omitted columns in AR6 Table 12.12 show most weather impacts are not expected to exhibit an anthropogenic signal through the end of this century.

Climatic Impact-driver Type	Climatic Impact-driver Category	Already Emerged in Historical Period
Heat and Cold	Mean air temperature	1
	Extreme heat	2
	Cold spell	4
	Frost	
Wet and Dry	Mean precipitation	
	River flood	
	Heavy precipitation and pluvial flood	
	Landslide	
	Acidity	
	Hydrological drought	
	Agricultural and ecological drought	
	Fair weather	
Wind	Mean wind speed	
	Severe wind storm	
	Tropical cyclone	
	Sand and dust storm	
Snow and Ice	Snow, glacier and ice sheet	
	Permafrost	
	Lake, river and sea ice	11
	Heavy snowfall and ice storm	
	Hail	
	Snow avalanche	
Coastal	Relative sea level	
	Coastal flood	
	Coastal erosion	
Open Ocean	Mean ocean temperature	
	Marine heatwaves	
	Ocean acidity	
	Ocean salinity	13
	Dissolved oxygen	14
Other	Air pollution weather	
	Atmospheric CO ₂ at surface	
	Radiation at surface	

High confidence of decrease	Medium confidence of decrease	Low confidence is direction of change	Medium confidence of increase	High confidence of increase
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Table 8.1: Reproduction of column 1 of Table 12.12, IPCC AR6 Working Group I report. Emergence of anthropogenic signal in historical period for CIDs shown. White: no signal detected. Blue and orange: change detected (decrease or increase) and confidence level as indicated in color legend.

As discussed in Chapter 6 natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trend reversals over time. Table 8.1 makes the related point that it is not currently possible to attribute changes in most extreme weather types to human influences. Taking wind as an example, the IPCC claims that an anthropogenic signal has not emerged in average wind speeds, severe windstorms, tropical cyclones or sand and dust storms, nor is one expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather.

8.6 Extreme event attribution (EEA)

Examining the IPCC's treatment of extreme weather and climate event attribution more broadly, AR6 provides an ambiguous assessment of the role of anthropogenic warming that differs between its chapters. Chapter 11 of WG1 states (Seneviratne *et al.*, 2021):

Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system.

By contrast, as noted in Section 8.5, Chapter 12 of WG1 (Table 12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions (Ranasinghe, 2021):

- High confidence in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere
- Medium confidence in a decrease in extreme cold events in Australia, Africa and most of northern South America where observations allow trend estimation
- No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones

While the overall issue of detecting changes in extreme weather events and their attribution remains ambiguous, most of the activity in this area relates to the attribution of particular extreme weather events. The most prominent effort is World Weather Attribution (WWA; worldweatherattribution.org), an international research initiative for extreme event attribution that purports to analyze how climate change influences the likelihood and intensity of extreme weather events. Their approach is to use large ensembles of regional climate models to compare an event in today's climate with one in a counterfactual pre-industrial climate without human influences.

WWA has a prominent public presence in linking extreme weather to climate change, with its press releases attracting considerable attention in public and policy discussions. However, the WWA's extensive promotion of non-peer-reviewed findings, its open admission to shaping analyses to serve litigation, and its methodological challenges have sparked controversies, with critics questioning the robustness and impartiality of their conclusions (Pielke Jr. 2024). Despite these issues, WWA's work continues to influence climate science and media narratives. Technical criticisms of the approach include a lack of a formal detection process; an implicit assumption that 100 percent of the post-industrial warming is caused by greenhouse gases; and a failure to adequately account for internal climate variability.

Because EEA is relatively new, many basic methodological issues have yet to be settled in the expert literature. An important challenge is the lack of data. Extreme events are by definition rare. Many analyses of extreme event types (including the U.S. National Assessment Reports) only evaluate data since 1950 or 1970. However, as emphasized by Chapter 6, many of the worst extreme weather and climate events in U.S. history occurred in the first half of the 20th century, including in the early 19th century. And if paleoclimate reconstructions are considered, it becomes very difficult for an event to pass thresholds of what is expected from natural variability, particularly if a reasonably sized geographic region is considered.

Another challenge is defining the event under study. There is a longstanding literature in statistics and econometrics on the challenge of analyzing data with outliers. The issue arises because a data series establishes a probability distribution defining the expected range of observations. If an outlier is observed it might indicate that the underlying process giving rise to the data distribution has changed (which in the weather context would mean that a climate change has been detected) or that the underlying process has multiple regimes each with a different probability distribution, in which case observing an outlier simply means we were temporarily in a different regime, but the system itself was unchanged. If a time series contains only a single outlier event at the end of the series it is not possible to determine which model is the correct one (Chen and Liu 1993). For instance, there might be an “ordinary” weather regime that yields a distribution of summer daytime highs in a particular coastal region, and a second “heatwave” regime that kicks in when an inland blocking event occurs, which yields a temperature distribution centered 15°C higher than the first one. A day with temperatures 13°C above normal would either be an extreme heat anomaly under the first regime or a somewhat cool event under the second, and we have no way in this case of knowing on statistical grounds which view is correct.

Visser and Petersen (2012) and Sardeshmukh *et al.* (2015) both point out that different distributions might fit observed data equally well but yield very different implications about the likelihood of a specific weather event. Visser and Petersen argue that, in view of the deep uncertainties of extreme weather analysis, drawing a connection between individual events and global climate change should be avoided. Furthermore, the existence of an outlier at the end of a data series poses the problem that estimates of the event probabilities will be biased whether the outlier is included or excluded (Barlow *et al.*, 2020). Methods to eliminate the bias have not yet been established, leading some experts (*e.g.* Miralles and Davison 2023) to argue that in settings in which a data series contains a single extreme event at the end, estimation of a return period for the extreme event will be so biased and uncertain that it should be avoided altogether.

We provide a case study of a recent high impact extreme event in the U.S. to illustrate the challenges and ambiguities in attributing the frequency and intensity of extreme weather events to human-caused warming.

8.6.1 Case study – 2021 Western North America heat wave

The 2021 Western North America heat wave was an extreme event that affected much of Western North America in late June 2021. Surface temperature records were set in Portland, OR (116°F; previous record 107°F) and Seattle, WA (108 °F; previous record 103°F) (Mass *et al.*, 2024).

The WWA team generated international headlines with their analysis, which provided the following attribution statements (WWA, 2021; Philip *et al.*, 2022):

- Based on observations and modeling, the occurrence of this heatwave was virtually impossible without human-caused climate change.
- The event is estimated to be about a one in 1000-year event in today’s climate.
- The event would have been at least 150 times rarer without human-induced climate change.
- This heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).

But an important counter to the first claim is that other researchers concluded from historical weather data that while a heat wave of the magnitude observed was indeed virtually impossible without anthropogenic climate change, it was also virtually impossible *with* climate change. Bercos-Hickey (2022) noted “these temperatures were virtually impossible under any previously experienced meteorological conditions, with or without global warming.” McKinnon and Simpson (2022) stated “the most likely explanation remains that the weather event itself was ‘bad luck.’” The 2023 Oregon Climate Assessment (Fleischman, 2023) concluded that the heat dome would have formed even without climate change and “There is no evidence that the highly unusual combination of weather features that drove the heat dome were made more likely by climate change, and climate models do not project an increase in the frequency of high-pressure ridges over the Pacific Northwest” (Fleischman, 2023, p. 49).

Mass *et al.* (2024) summarizes the proximate sequence of compound events leading to the heat wave. There was a record-breaking mid-tropospheric ridge over the Pacific Northwest, forced by a tropical disturbance in the western Pacific. This produced record-breaking mid-tropospheric temperatures, strong subsidence in the lower atmosphere, low-level easterly flow that produced downslope warming on regional terrain and the removal of cooler marine air, and an approaching low-level trough that enhanced downslope flow. The event occurred at a time of maximum solar insolation, and drier-than-normal soil moisture. Using a storyline approach, Mass *et al.* assessed that there was no trend in drought and dry soils in the Pacific Northwest; there is no evidence of global warming producing stronger ridges of high pressure, and no observed trend in heat waves or record temperatures in the region. They concluded that although anthropogenic warming might have contributed as much as 2°F to the magnitude of the event, there is little evidence of further amplification of the event from increasing greenhouse gases.

Bercos-Hickey *et al.* (2022) conducted a statistical analysis of a model-based attribution study of this heat wave. Because the event is a far outlier and far above the bounds of Generalized Extreme Value distributions fitted from historical data, they concluded that estimates of return times, quantitative changes in event magnitude and frequency, and probability of the extreme temperatures such as provided by the WWA are not accurate and should be interpreted as having low confidence. They found that hindcast attribution methods using an ensemble of regional climate models, combined with Pearl (2009) causal inferences, can provide limited and conditional information about the magnitude of the human influence on this heatwave - they provided a more highly constrained estimate that human activities caused a ~1.4°F–1.8°F increase in the daily maximum temperatures.

Zeder *et al.* (2023) also concluded that the methods employed by Philip *et al.* (2022, the WWA analysis) tend to overstate the rarity of extreme heat waves, leading to a biased perception of the effect of climate change on the heatwave event: “The tendency to overestimate the return period of observed extreme heatwave events may fuel the impression that seemingly impossible heatwave extremes are currently clustering at an unprecedented rate.”

The 2021 Western North America heatwave was a rare and unprecedented compound weather event that broke century-old temperature records by as much as 9°F. While the WWA team received worldwide publicity for their rapid attribution claims blaming anthropogenic climate change, subsequent peer-reviewed analyses showed that the event was caused by rare meteorological conditions that were not made more probable by global warming.

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PART III: IMPACTS ON ECOSYSTEMS AND SOCIETY

9 CLIMATE CHANGE AND U.S. AGRICULTURE

Chapter summary

There has been abundant evidence going back decades that rising CO₂ levels benefit plants, including agricultural crops, and that CO₂-induced warming will be a net benefit to U.S. agriculture. The increase in ambient CO₂ has also boosted productivity of all major U.S. crop types. Various attempts to argue that CO₂-induced warming will harm agriculture do not hold up under scrutiny.

9.1 Econometric analyses

Econometric analyses of the effects of climate change on agriculture have sought to integrate information about long term crop yield changes in response to temperature and precipitation changes under assumptions about adaptive behavior by farmers. One method focuses on variations in agricultural land values. The rationale is that if climate change is a long-term net benefit for agriculture it should be capitalized into higher market values for agricultural land, and vice versa. While individual crops might benefit from, or be harmed by, climate change, once the adaptative responses of farmers are considered the value of farmland represents an index of whether the changes are expected to be beneficial or not. Mendelsohn *et al.* (1994) examined the relationship between historical climatic variations on agricultural land values and concluded global warming would be slightly beneficial to American agriculture.

The Mendelsohn *et al.* method, called Ricardian analysis after David Ricardo, the 19th century British economist who pioneered the study of land values, attracted subsequent criticism from authors who argued it failed to account for differences in land values attributable to fixed locational characteristics like soil quality, and non-climatic changes including nearby urbanization. Deschênes and Greenstone (2007) looked at agricultural profits instead of land values and reached conclusions similar to Mendelsohn *et al.* (1994), namely that past climatic variations had relatively little effect on farm profitability and that warming would likely yield small overall benefits for the U.S. agricultural sector. However, a subsequent exchange with critics led them (Deschênes and Greenstone 2012) to revise their conclusions and project potentially large losses in U.S. agriculture due to climate warming.

Burke and Emerick (2016) looked at temperature variations over 1980 to 2000 and argued that farmers were not as able to adapt to temperature changes as the Ricardian method assumes and that climate change would have large negative impacts on corn and soy yields. Schlenker and Roberts (2009) similarly argued that yield gains to past warming would not carry over to the future and corn and soy yields would sharply decrease this century due to climate change.

Two recent studies have argued that pessimistic findings such as these are not robust. Ortiz-Bobea (2019) argued that land values aggregate farm and non-farm influences and the latter need to be filtered out. He developed a data set using cash rents for agricultural activity as a measure of land value specifically for farming activity. Whereas the land value model implied future losses under climate warming, the same model estimated using cash rents did not, leading the author to conclude the pessimistic results were due to using an inaccurate measure of the returns to farming activity. Bareille and Chakir (2023) assembled a large data base on farm sale prices in France for properties that sold twice between 1996 and 2019. They could replicate pessimistic results showing negative effects of warming on agricultural land values using conventional econometric modeling. But by taking advantage of the repeat sales data, which provides information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture. The authors concluded that, taking adaptation into account, a warming climate would yield positive benefits for French agriculture that were between two and

20 times larger than had previously been estimated. On average, with full adaptation, they concluded that climate changes under the medium RCP4.5 scenario could double the value of French farmland by 2100.

A major deficiency of all these studies, however, is that they omit the role of CO₂ fertilization. Climate change as it relates to this report is caused by GHG emissions, chiefly CO₂. The econometric analyses referenced above focus only on temperature and precipitation changes and do not take account of the beneficial growth effect of the additional CO₂ that drives them. As explained in Chapter 2, CO₂ is a major driver of plant growth, so this omission biases the analysis towards underestimation of the benefits of climate change to agriculture.

9.2 Field studies of CO₂ enrichment

One of the ways the effect of CO₂ on crop growth has been studied is through “free air enrichment experiments” or FACE plots, in which small sources of CO₂ are placed in fields surrounding plants and the growth response to elevated CO₂ under varying weather conditions are recorded. Ainsworth *et al.* (2020) summarizes results from about 250 such studies. They found that elevation of CO₂ by 200 ppm caused an average 18 percent increase in crop yield in C3 plants. C4 plants exhibited benefits mainly under drought conditions.

In addition to FACE plot experiments there have been thousands of laboratory experiments on the effects of CO₂ on all kinds of plant growth. Here we review some of the results on key U.S. agricultural crops.

Soybean

Studies on the impact of elevated CO₂ on Soybean (*Glycine max* (L.) Merr.) plants in the water-deficient region of Huang-Huai-Hai Plain, China, showed that elevated CO₂ concentrations improved photosynthesis rate, water use efficiency, and growth Li (2013) under both normal conditions and drought conditions. The CO2Science.org website reports on 108 published experiments between 1985 and 2019 exposing soybean to enriched CO₂ levels. Converted to a +300ppm common scale the average growth benefit was +50.9 percent. There were also ten studies reporting on +600 ppm CO₂ enrichment, which increased photosynthesis by an average of 90.3%.

Maize (corn)

The CO2Science.org website reports on 28 published experiments between 1983 and 2018 exposing corn (*Zea mays* L.) to enriched CO₂ levels. Converted to a +300ppm common scale the average growth benefit was +23.7 percent. Corn also benefits from increased drought tolerance under elevated CO₂. An experimental study (Allen Jr., 2011) exposed plants to water stress conditions in sunlit controlled-environment chambers at 360 ppm (ambient) and 720 ppm (elevated) CO₂. The drought stress caused a 41 percent loss of growth under ambient CO₂ but only a 13 percent loss under elevated CO₂.

Wheat

The CO2Science.org website reports on 92 published experiments between 1983 and 2020 exposing common wheat (*Triticum aestivum* L.) to enriched CO₂ levels. Converted to a +300ppm common scale the average growth benefit was +67.6 percent. Blandino (2020) measured both the yield and nutritional quality of an “improver” hybrid wheat variety and its parents under elevated CO₂ levels (+166 ppm). They reported a grain yield increase of +16 percent but a 7 percent decrease in grain protein levels. But they also found that the food quality of different wheat varieties responded differently to elevated CO₂ levels, so that with proper varietal selection, growers could select wheat types that best take advantage of the elevated CO₂.

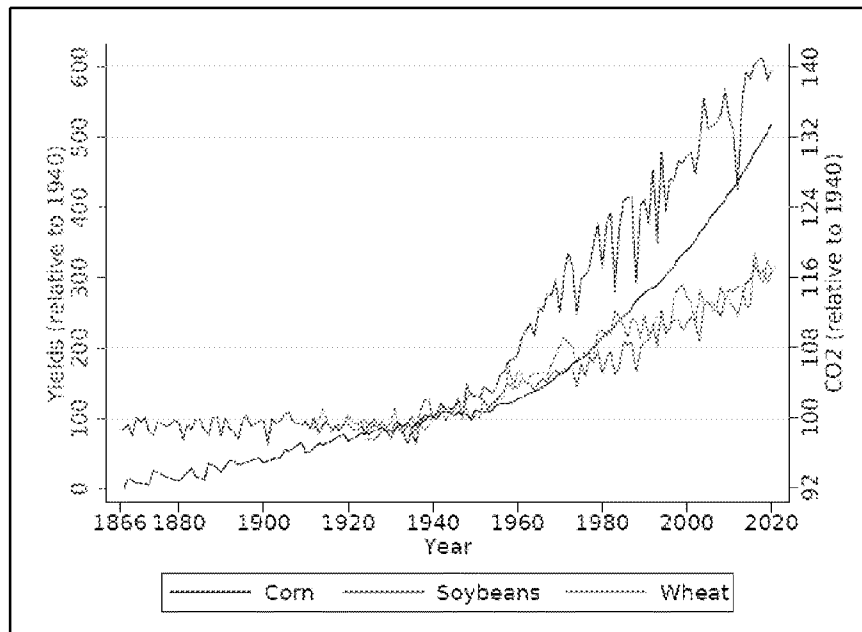


Figure 9.1: U.S. average CO₂ levels and yields of corn, soy and wheat all normalized so 1940=100. Source: Taylor and Schlenker (2021)

Further evidence

A 2021 report from the U.S. National Bureau of Economic Research (Taylor and Schlenker 2021) used satellite-measured observations of outdoor CO₂ levels across the United States, matched to county-level agricultural output data and other economic variables. After controlling for the effects of weather, pollution and technology the authors concluded that CO₂ emissions had boosted U.S. crop production since 1940 by 50 to 80 percent, attributing much larger gains than had previously been estimated using FACE experiments. They found that every ppm of increase in CO₂ concentration boosts corn yields by 0.5 percent, soybeans by 0.6 percent, and wheat by 0.8 percent.

Beyond growth benefits, extra CO₂ boosts plant resilience to dryness. Deryng *et al.* (2016) surveyed evidence on crop water productivity (CWP, the yield per unit of water used), drawing attention to the potential for CO₂ both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data on crop yield changes for maize (corn), wheat, rice and soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO₂ fertilization predicted CWP losses but CO₂ fertilization more than offset them; once fertilization was taken into account, all regions showed a net CWP gain. Deryng *et al.* also reported that negative yield impacts on wheat and soybean were fully offset by CWP gains and mitigated by up to 90 percent for rice and 60 percent for maize. Similarly, Cheng *et al.* (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO₂ uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryng *et al.* (2016) assumed that climate change would “exacerbate water scarcity”. It is noteworthy that while models predict drylands will expand under climate warming, observations show the opposite: greening is happening even in arid areas. Zhang *et al.* (2024) report that due to increased CO₂ levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”; increased desertification will happen in at most 4 percent of currently arid areas.

9.3 Crop modeling meta-analyses

Notwithstanding the abundant evidence for the direct benefits of CO₂ and of CO₂-induced warming on crop growth, in 2023 the U.S. Environmental Protection Agency (EPA 2023) boosted its estimate of the Social Cost of Carbon (SCC) about five-fold based largely on a very pessimistic 2017 estimate of global agricultural damages from climate warming (Moore *et al.*, 2017). One of the two damage models used by the EPA attributed nearly half of the 2030 SCC to projected global agricultural damages based on the Moore *et al.* (2017) analysis. This study was a meta-analysis of crop model studies simulating yield changes for agricultural crops under various climate warming scenarios. Moore *et al.* projected declining global crop yields for all crop types in all regions due to warming.

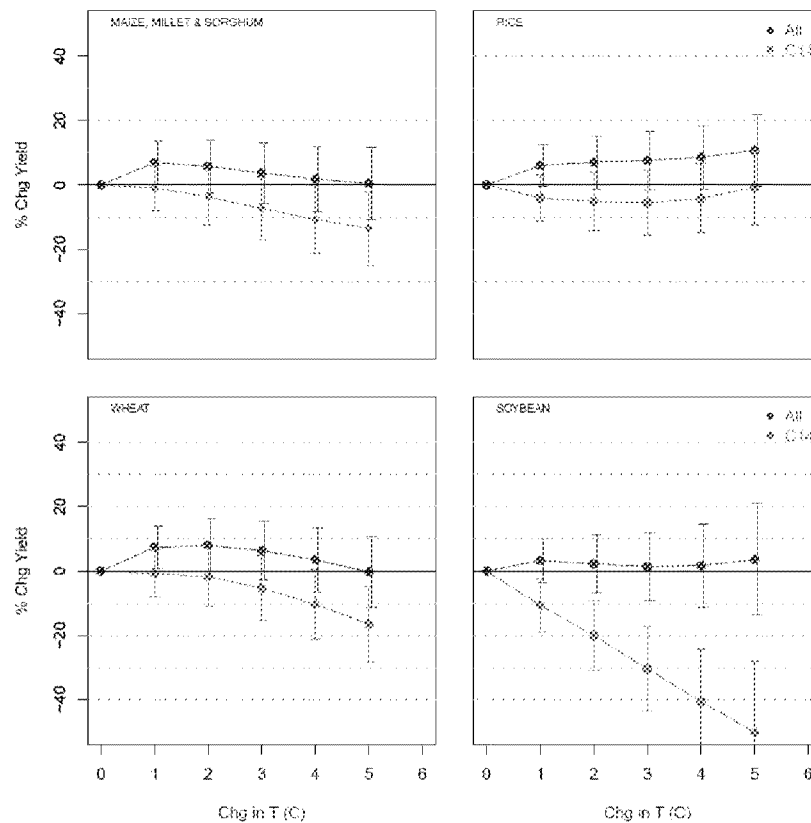


Figure 9.2 Crop yields under CO₂-induced climate warming. Blue: as published in Moore *et al.* (2017). Green: after including omitted data. Source: McKittrick (2025).

McKittrick (2025) re-examined the Moore *et al.* database and found that, while it claimed to cover 1,722 studies, only half the entries ($N=862$) had complete records, so that the sample available for regression analysis was much smaller than both studies indicated. McKittrick noted that the records most commonly missing were the changes in ambient CO₂ and found that in many cases these could be recovered from the underlying studies or the original climate scenario tables, thereby increasing the usable sample size by 40 percent. The crop yield projections incorporating the newly available data changed considerably. As shown in Figure 9.2, whereas the partial data set implied warming would decrease yield (blue lines), the complete data set implied constant or increase global yields, even out to 5°C warming (green lines).

9.4 CO₂ fertilization and nutrient loss

Evidence has shown that CO₂-induced biomass gains are sometimes accompanied by reductions in the concentrations of protein and other key nutrients such as iron and zinc (Ebi *et al.* 2021). Some experimental evidence has shown that the rising temperatures expected to accompany higher CO₂ levels will offset this loss (Köhler *et al.* 2019) although the evidence for this is mixed, as is the evidence that nutrient dilution observed to date is attributable to higher CO₂ (Ziska 2022). If nutrient dilution does occur under rising CO₂ levels there are several adaptive strategies that could be pursued.

First, selective breeding to raise micronutrient content is already long established (Saltzman *et al.* 2017) and has proven to be a cost-effective agronomic strategy (Ebi *et al.* 2021). Strategies can include both conventional breeding and genetically-modified organisms. An example of the latter is Golden Rice, which contains elevated levels of beta-carotene to boost biosynthesis of vitamin A in the human body. Optimal strategies will be location-specific because they vary by crop, climate and soil type (Ebi *et al.* 2021). Second, fortification of food products with micronutrients is already routine. Folic acid (a B vitamin) is added to flour and many other foods; iodine is added to table salt, most commercial breakfast cereals are fortified with iron and numerous vitamins, *etc.* Third, dietary supplements in the form of multivitamin tablets are inexpensive, widely-available and routinely consumed.

One concern about reliance on adaptive strategies is whether they are feasible in low-income countries. Micronutrient deficiency is already a problem in the developing world and dietary supplements have proven to be an effective low-cost response (Ebi *et al.* 2021). It should also be noted the IPCC emission scenarios that generate high levels of warming do so on the basis of high levels of income growth. The SSP scenarios³ assume that, compared to 2005 levels, global per capita income will double by 2100 in the lowest growth case (SSP3), and in the highest emission case (SSP5) global per-capita income will grow nearly 16-fold. In that scenario even the poorest regions (Africa and the Middle East) end up with a per capita income of about US\$126,000, 70 percent higher than current U.S. per capita income (about US\$75,000). Consequently the same scenarios in which CO₂ levels increase the most are also those in which global poverty is largely eliminated, in which case all countries would be able to afford dietary supplements as necessary to address micronutrient deficiencies, if they arise and cannot be addressed using on-farm agricultural strategies.

In summary, there is abundant evidence going back decades that rising CO₂ levels benefit plants, including agricultural crops, and that CO₂-induced warming will be a net benefit to U.S. agriculture. To the extent nutrient dilution occurs there are mitigating strategies available that will need to be researched and adapted to local conditions.

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³ See compilation at [Our World in Data](#).

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10 MANAGING RISKS OF EXTREME WEATHER

Chapter summary

Trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. The U.S. economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages. Heat-related mortality risk has dropped substantially due to adaptive measures including the adoption of air conditioning, which relies on the availability of affordable energy. U.S. mortality risks even under extreme warming scenarios are not projected to increase if people are able to undertake adaptive responses.

10.1 Socioeconomic context

Risks from human-caused climate change are affected by natural weather and climate variability and are dominated by the exposure of wealth in coastal and other disaster-prone regions and vulnerabilities of poorer populations. The evolution of climate risk in the U.S. has been dominated by societal factors, rather than by changes to the actual weather and climate hazards. Deaths from weather disasters have decreased substantially since 1900, even as U.S. population grew from 76 million in 1900 to over 331 million in 2020 (Goklany 2011). For example, the Galveston hurricane killed over 8,000 people in 1900 (0.01 percent of the U.S. population), whereas the worst recent disaster, Hurricane Katrina in 2005, killed 1800 people (or 0.0006 percent of the U.S. population) (NOAA National Hurricane Center 2025; U.S. Census Bureau 2025).

Technological advances have substantially reduced losses from extreme weather events. Early warning systems, satellite monitoring, and improved weather forecasting have reduced deaths, although exact numbers are hard to quantify (Deryugina and Hsiang 2023). U.S. weather forecasting has been estimated to reduce losses from weather events with an annualized benefit of \$31.5B, protecting lives, property, and supporting agriculture and transportation (NRC 2010). Improved hurricane forecasts have reduced pre- and post-landfall spending, with annual per hurricane cost reductions estimated at \$5B (Molina and Rudik 2024).

Infrastructure improvements have contributed to substantial reductions in losses from extreme weather events. Building codes, such as those implemented in Florida after Hurricane Andrew (1992), have reduced losses by ensuring structures can withstand high winds and floods. Homes built after 2002 showed minimal damage during Hurricane Michael (2018), unlike older homes (FEMA 2020). Sea walls, like the Galveston Seawall, protect against wave action and storm surge. The New Orleans Hurricane and Storm Damage Risk Reduction System successfully mitigated storm surge during Hurricane Isaac (2012) (Battelle Memorial Institute 2013). Inland dams in the U.S. help control flooding by storing excess water during heavy rains. It is estimated that the Tennessee Valley Authority (TVA) dams prevent about \$309M in annual flood damage in the TVA region and along the Ohio and Mississippi Rivers (TVA, 2025). During Hurricane Helene (2024), TVA's strategies prevented approximately \$406M in potential damages (APPA 2024).

10.2 Data challenges

Since 1980, NOAA has provided a count of annual U.S. weather-related disasters that it estimates to have exceeded \$1 Billion (inflation adjusted), showing a substantial increase starting in 2008. NOAA and other government officials have cited the upward trend in the Billion Dollar Disaster series as evidence that climate change is making extreme weather worse (Pielke Jr., 2024). But over time, population and wealth have increased dramatically in the U.S., so when an extreme weather or climate event occurs, there is more damage even if there is no underlying trend in the frequency or intensity of extreme weather. Pielke Jr. (2024) demonstrates that losses per weather disaster as a proportion of GDP have decreased by about 80 percent since 1980, as shown in Figure 10.1. Pielke Jr. (2024) also argued that in addition to relying on opaque data sources and unreported adjustments, NOAA failed to normalize its Billion Dollar Disaster data series properly for changes in population exposure and wealth. In May 2025 NOAA announced it has withdrawn the Billion Dollar Disaster product from publication (Pielke Jr., 2025).

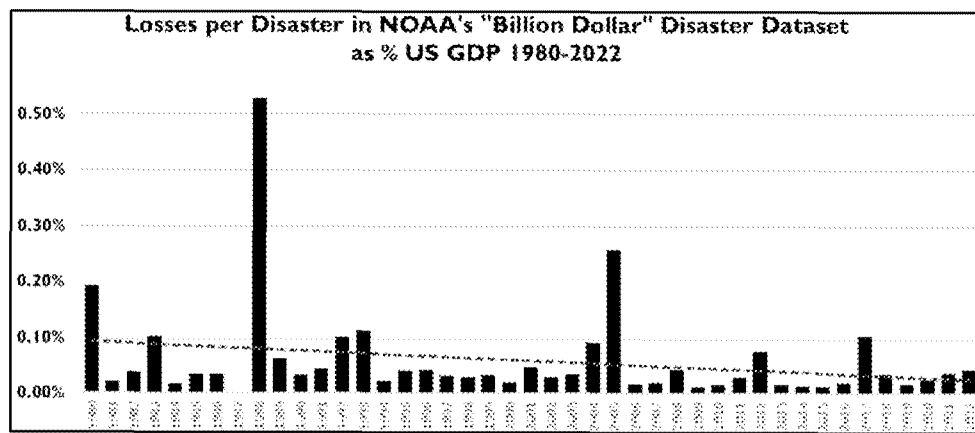


Figure 10.1: Losses per disaster as a % of Gross Domestic Product in NOAA's billion-dollar disaster dataset (the version downloaded in July 2023), 1980 to 2022. Source: (Pielke, Jr. 2024)

In summary, trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. Finally, the U.S. economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages.

10.3 Mortality from temperature extremes

10.3.1 Heat and cold risks

Changes in temperature extremes are among the most certain impacts expected in a warming world. It stands to reason that extreme heat events would likely become more frequent while extreme cold events would become less frequent. This pattern is evident in the historical period, though not in the continental U.S. (Chapter 6), and is expected to continue with further warming.

Mortality during heat extremes is typically caused by heat stroke and heat exhaustion, while mortality during cold extremes typically stems from hypothermia and heart strain. Global mortality is substantially greater for cold conditions than for hot conditions (Zhao et al 2021, Ritchie 2024). Unlike with heat-related mortality, cold-weather risks set in even at moderately cold conditions (Gasparini *et al.* 2015, Lee and Dessler 2023). The U.S. EPA (citing data from the Centers for Disease Control) reports that on average over 1999 to 2015 there were 2.2 deaths per million Americans for which cold was listed as the main underlying cause and an additional 2.4 deaths per million for which cold was listed as a contributing factor (EPA 2025). By contrast there were 1.3 deaths per million for which heat was the main cause and an additional 0.8 per million for which it was a contributor. By this metric cold accounts for approximately double the weather-related deaths as does heat.

Epidemiological methods that consider correlational evidence, not just death certificate reports, indicate the cold/warm ratio might be much higher. A 13-country study of 74 million deaths from 1985 to 2012 estimated that, on average, 7.7 percent of deaths were attributable to sub-optimal temperatures, of which 7.4 percent were attributable to cold and only 0.4 percent were attributable to heat (Gasparini *et al.* 2015). In other words, cold weather killed 18.5 times as many people as did hot weather.

Figure 10.2 shows the distribution of results from Gasparini *et al.* (2015) by country. For the United States the fraction of deaths attributable to temperature was 5.9 percent, of which 5.5 percent was due to cold, thus cold weather killed 14 times as many people as hot weather.

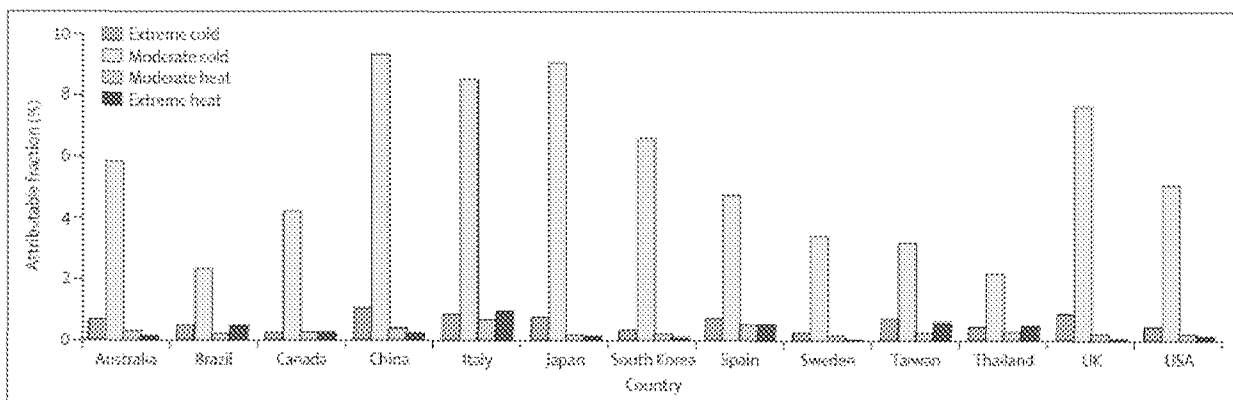


Figure 10.2. Mortality attributable to extreme and moderate cold and heat by country. Source: reproduced from Gasparini *et al.* (2015).

There is strong evidence that people adapt to weather risks. Lee and Dessler (2023) reported that 86 percent of temperature-related deaths across 40 cities in the U.S. were due to cold-related mortality, and that due to adaptation the relative risk of death declined in hot and cold cities alike as seasonal temperatures increased. Allen and Sheridan (2018) found that short, early-season cold events were 2 to 5 times deadlier than hot events, but the mortality risk of both cold and hot extremes drops to nearly zero if the events occur late in the season.

Davis *et al.* (2003) examined heat-related mortality in 28 U.S. cities from the 1960s to the end of the 1990s and found that heat-related mortality declined by three-quarters over the sample period. Bobb *et al.* (2014) examined mortality data for 106 million people in over 100 cities U.S. cities and found a 60 percent decline in average heat-related mortality over the period 1987–2005, from 51 per thousand deaths to 19. They furthermore found that the greatest drop was among seniors over the age of 75. In a study of 42 million

deaths in 211 U.S. cities from 1962 to 2006. Nordio *et al.* (2015) found a more than 90 percent decline in the risk of mortality from excess heat.

In the context of large declines in heat-related mortality, rising temperatures are associated with a net saving of lives since they reduce mortality from cold events. The IPCC AR6 Working Group 2 Chapter 16.2.3.5 (O'Neill *et al.* 2022) acknowledges that heat-related mortality risk is declining over time:

Heat-attributable mortality fractions have declined over time in most countries owing to general improvements in health care systems, increasing prevalence of residential air conditioning, and behavioral changes. These factors, which determine the susceptibility of the population to heat, have predominated over the influence of temperature change.

Yet the IPCC misrepresents the overall situation in its AR6 Synthesis report. Section A.2.5 of that document states: “In all regions increases in extreme heat events have resulted in human mortality and morbidity (*very high confidence*).” But it is silent on the larger decline of deaths during extreme cold events.

The observed decline in U.S. heat-related mortality has been specifically attributed to adaptation. Wang *et al.* (2018) exploited the spatial variability of heatwave-related mortality across 209 U.S. cities from 1962 to 2006. While simple correlation appeared to imply an increase in mortality risk during heatwaves, accounting for adaptation to heatwave intensity caused the effect to fall to near zero and become statistically insignificant. They used the results of their epidemiological model to project heat-related mortality out to 2050 under four RCP warming scenarios (including RCP8.5) with and without adaptive behavior. Assuming people continue to adapt to the heatwave risks in the regions in which they live. Wang *et al.* (2018) project not only no increase in heat-related mortality, but an overall mortality *decrease* for the U.S. as a whole. They conclude that

Ignoring adaptation would result in a substantial overestimate of future mortality related to heat waves... Accounting for adaptation, the overall heat-related mortality by 2050 would not change substantially over time compared to 2006.

10.3.2 Mortality risks and energy costs

A 2016 study of U.S. long term mortality risks associated with temperature variations (Barreca *et al.* 2016) showed that increases in mortality across the U.S. are associated with both cold weather and hot weather. But over time, the introduction of electricity and the adoption of central heating and air conditioning (AC) dramatically reduced both risks, especially those associated with hot weather. Prior to 1960, a day above 90°F (32°C) added 2.2 percent to the average mortality risk rate, but after 1960 the same weather added only 0.3 percent to mortality risk, an 85 percent reduction. Prior to 1960 temperatures below 39°F (4°C) added about 1 percent to mortality risk but after 1960 the same weather only added about half that amount. Adaptation through conventional household improvements dramatically reduced public vulnerability to weather extremes. The entire reduction in hot weather mortality was attributable to widespread adoption of indoor AC, which depended on the availability of reliable and affordable electricity.

The corollary of this finding is that the use of heating and cooling systems depends on energy being affordable. Doremus *et al.* (2022) showed that wealthy and poor households in the U.S. adjust their energy expenditures at similar rates in response to moderate temperature swings, but not in response to extreme temperature swings. When temperatures swing to very cold levels (< 5°C) energy spending in high-income

households rises by 1.2 percent but in low-income households by only 0.5 percent. On very hot days (>30°C) electricity spending in high-income households rises by 0.5 percent but does not change at all in low-income households. The latter result is observed even in subsamples where all households have AC. The implication is that even with widespread adoption of home heating and cooling systems, inability to afford energy leaves low-income households exposed to weather extremes.

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11 CLIMATE CHANGE, THE ECONOMY, AND THE SOCIAL COST OF CARBON

Chapter summary

Economists have long considered climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in AR5. Mainstream climate economics has recognized that CO₂-induced warming might have some negative economic effects but they are too small to justify aggressive abatement policy and that trying to “stop” or cap global warming even at levels well above the Paris target would be worse than doing nothing. An influential study in 2012 suggested that global warming would harm growth in poor countries, but the finding has subsequently been found not to be robust. Studies that take full account of modeling uncertainties either find no evidence of a negative effect on global growth from CO₂ emissions or find poor countries as likely to benefit as rich countries.

Social Cost of Carbon (SCC) estimates are highly uncertain due to unknowns in future economic growth, socioeconomic pathways, discount rates, climate damages, and system responses. The SCC is not intrinsically informative as to the economic or societal impacts of climate change. It provides an index connecting large networks of assumptions about the climate and the economy to a dollar value. Some assumptions yield a high SCC and others yield a low or negative SCC (i.e. a social benefit of emissions). The evidence for or against the underlying assumptions needs to be established independently; the resulting SCC adds no additional information about the validity of those assumptions. Consideration of potential tipping points does not justify major revisions to SCC estimates.

11.1 Climate change and economic growth

11.1.1 Overview

It has long been noted that economies tend to do poorly in very cold and very hot regions, with the optimum somewhere in between (Nordhaus, 2006). Temperature-sensitive economic activity migrates, whenever possible, to where it is best suited, and society adapts to the local climate. Based in part on these observations, in 1992 Thomas Schelling, then President of the American Economic Association, argued that any effects of climate change on U.S. economic activity would be small relative to the many other changes that would happen (Schelling 1992).

... Manufacturing rarely depends on climate, and where temperature and humidity used to make a difference, air conditioning has intervened. When Toyota chooses among Ohio, Alabama, and Southern California for locating an automobile assembly, geographical considerations are important, but not because of climate... Finance is little affected by climate; similarly for health care, or education, or broadcasting. Transportation can be affected, but improvements in all-weather landing and take-off in the last 30 years are greater than any differences that climate makes. If the average effect is a warming, iced waterways and snow removal may decline in importance. Construction is affected, mainly by cold, and if the average effect is in the direction of warming, construction may benefit slightly.

It is really agriculture that is affected. But even if agricultural productivity declined by a third over the next half century, the per capita GNP we might have achieved by 2050 we would achieve only in 2051. ...

I conclude that in the United States, and probably Japan, Western Europe, and other developed countries, the impact on economic output will be negligible and unlikely to be noticed.

Thirty years later virtually the identical point was made by the IPCC itself in the Fifth Assessment Report (Arent *et al.* 2014, emphasis added)

For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers. Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change.

Evidence since AR5 does not change this assessment. Mohaddes *et al.* (2023) found that warm weather shocks have small negative effects on U.S. state-level output but not income, while cold weather shocks negatively affect both and the impacts are about four times larger, implying a shift to warmer conditions would, if anything, yield a net economic benefit for the U.S.

These statements are validated by experience. Since 1900, the average global surface temperature anomaly warmed 1.3°C, about as much as the IPCC predicts will occur in the next century under a moderate emissions scenario. But even as the globe warmed and the population quintupled, humanity prospered as never before. For example, global average lifespan went from thirty-two years to seventy-two years, economic activity per capita grew by a factor of seven, and the death rate from extreme weather events plummeted by a factor of fifty.

While extreme weather events are costly, in all modern economies they are becoming steadily less and less important (Formetta and Feyen, 2019). Since 1990 weather-related disaster losses have declined as a proportion of global GDP (Pielke Jr , 2018, 2020) as have mortality risks (Formetta and Feyen, 2019). While economic weather-related insurance payouts are rising, this is fully explained by the growth in the size of the economy and the value of the insured asset stock. Past increases in episodes extreme weather have not had a significant effect (positive or negative) on the market value of insurance firms (Hu and McKittrick, 2015). Nor have past extreme weather events had a significant effect on U.S. banks' performance (Blickle *et al.*, 2021); warming has even been shown to be beneficial for the finance and insurance sector (Mohaddes *et al.* 2023). Figure 11.1 below is illustrative. For these reasons, economists have long been reluctant to endorse attempts to “stop” climate change or even aggressively reduce GHG emissions because the costs would not be worth it. As one critic of the economics of climate policy put it (Storm 2017):

Mainstream climate economics takes global warming seriously, but perplexingly concludes that the optimal economic policy is to almost do nothing about it... The contrast is striking. While climate science is sending out loud-and-clear messages that fossil-fuel disinvestment must start now, letting go of coal and oil and diverting resources into renewable energy technology systems, to keep warming below the 2°C limit (IPCC 2014), mainstream climate economics claims that overly ambitious climate targets will unnecessarily hurt the economy and immediate de-carbonization is too expensive. Most climate economists thus recommend humanity to just wait-and-see.

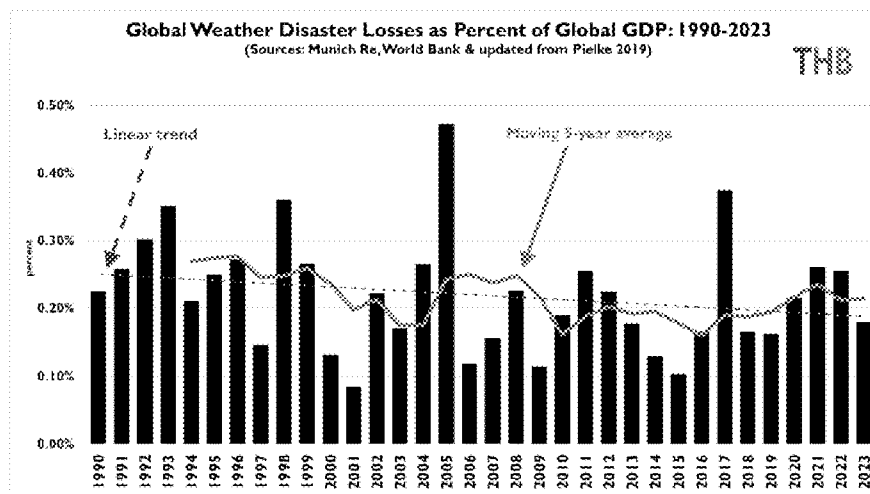


Figure 11.1 Global weather losses as a fraction of GDP. Source: Pielke Jr. (2023)

The mainstream economics position on the climate policy question is best represented by the findings over the past three decades from Integrated Assessment Models (IAMs) of climate change policy, for which Yale economist William Nordhaus was awarded the 2018 Nobel Memorial Prize in economics. IAMs combine economic, climate, and social data into a unified framework for simulating climate damages and evaluating the optimal policy response (Resources for the Future, 2025). Nordhaus' work has generally supported modest global climate policy, with aggressive measures largely deferred to later in the century. Nordhaus developed the so-called Dynamic Integrated Model of the Climate and Economy model, or DICE, in the early 1990s (Nordhaus, 1993) to study the interaction between climate change, climate policy, and global economic growth over long times. DICE assumes global emission control can be coordinated at no cost and asks what the optimal policy target should be. The climate component of the DICE model is based on simplified climatological modeling. The version of DICE at the time of Nordhaus' Nobel Prize award was described in Nordhaus (2018); it had a climate sensitivity parameter of 3.1°C for CO₂ doubling, consistent with the best estimate in IPCC reports (3.0°C).

The baseline (no policy) scenario incurs only \$0.4T in global abatement costs and leads to \$134.2T (trillion dollars) in global climate damages for a total cost of \$134.6T. The climate model component of DICE projects 4.1°C warming by 2100 relative to preindustrial temperatures. Note that this is a higher estimate of warming than many IPCC climate models.

The Optimal Policy scenario barely deviates from the business-as-usual path. It aims for +3.5°C warming, in other words we modestly scale back fossil fuel use and otherwise just live with almost all the warming. This suggests that most CO₂ emissions are less harmful than the policies that would be necessary to abate them. Trying to prevent warming causes costs quickly to outstrip the benefits. Pursuing a goal of capping warming at 2.5°C creates total costs of \$177.8T, which is \$43.2T worse than doing nothing at all. Nordhaus didn't evaluate trying to reach a Paris-type target of 1.5°C warming but it would be even more costly.

A subsequent edition of DICE includes higher assumed damages from warming which, not surprisingly leads to more aggressive policy recommendations, as explained in the section below on the Social Cost of Carbon.

11.1.2 Empirical analysis of climate change and economic growth

Many other studies have used econometric methods applied to historical data, instead of IAMs, to study the potential impact of climate change on economic growth. Dell *et al.* (2012, herein DJO12) was an influential study that used a multi-country panel of national-level data spanning 1950 to 2005, in which they matched climate and economic data by averaging temperature from the local grid cell level up to the national level using population weights. They found that warming yields an insignificant positive effect on income growth in rich countries but a significant negative effect in poor countries. Moore and Diaz (2015) modified the DICE model to take that finding into account and concluded that it implied a dramatically higher Social Cost of Carbon due to the compounding effects of income loss over time.

A large subsequent literature has debated the robustness of the DJO12 findings. Burke *et al.* (2015) analyzed a global panel with temperatures averaged up to the national level and found a negative effect on growth from warming in rich and poor countries alike when the national average temperature is above 13°C. Zhao *et al.* (2018) used the G-Econ data set of Nordhaus (2006), which breaks economic activity down to the grid cell level, replicated DJO12-type results on the same subset of countries as used in DJO12 but then showed that on the full global sample warming increases growth in rich countries and poor countries alike, though the positive effect in the latter group is confined to where local temperatures are below about 16°C. Greßer *et al.* (2021) developed a regional economic data set for 1,542 sub-national regions around the world between 2005 and 2015 and found temperature had no effect on growth. Yang *et al.* (2023) updated the DJO12 data set and applied an estimator robust to mixed sample frequencies, finding that while temperature shocks exerted a temporary effect on income levels, they did not have a significant lasting effect on growth rates.

Newell *et al.* (2021) noted that there is no underlying theory to guide econometric model specification in this literature. Taking into account the arbitrary choices of which explanatory variables to include they identified over 800 possible model specifications. Using the Burke *et al.* (2015) data they used an estimation method that accounts for model uncertainty and found that the model form preferred by Burke *et al.* (2015), which implied negative effects of warming on growth even in rich countries, is explicitly excluded by the optimal model selection algorithm. Overall they could not detect a temperature effect on GDP or GDP growth, and they estimated the 95 percent confidence interval for the impact on global growth as of 2100 even under the exaggerated RCP8.5 warming scenario spans –86 percent to +388 percent. In other words the net effect is likely positive but too uncertain to distinguish from zero.

Barker (2023) criticized the DJO12 assumption that countries can be grouped into fixed “poor” and “rich” categories based on their incomes many decades ago. He noted that many countries were once poor but became rich over time, and if this is considered the original temperature effects reported by Dell *et al.* became small and insignificant.

Berg *et al.* (2023) argued that countries shouldn’t be grouped into large Rich/Poor categories because they are too heterogeneous. They instead estimated country-specific temperature response coefficients then grouped countries with similar response coefficients into small panels. They separately estimated responses to global and idiosyncratic local temperature shocks to better identify the climate signal in weather data. Overall, they found countries experiencing negative effects of warming on growth outnumbered those experiencing positive effects, but only temporarily: eventually the effects reverse such that about twice as many countries experience a net positive growth effect. They also found global (as opposed to local) temperature changes are much more likely to benefit growth in poor countries than rich ones. In a simulation to 2100, even using the extreme RCP8.5 scenario, they computed the average global GDP loss would be only 1.9 percent compared to a scenario with no warming. That is, instead of the economy growing 400 percent it would grow 392%. The implication of Nordhaus’ earlier analysis is that trying to prevent the warming would lead to far less than 392 percent growth.

To summarize, economists consider climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in the Fifth Assessment Report. Mainstream climate economics has recognized that CO₂-induced warming might have some negative economic effects but they are too small to justify aggressive abatement policy, and trying to “stop” or cap global warming even at levels well above the Paris target would be worse than doing nothing. An influential study in 2012 suggested that global warming would harm growth in poor countries but the finding has subsequently been found not to be robust (Tol 2024). Studies that take full account of modeling uncertainties either find no evidence of a negative effect on global growth from CO₂ emissions or find poor countries as likely to benefit from it as rich countries.

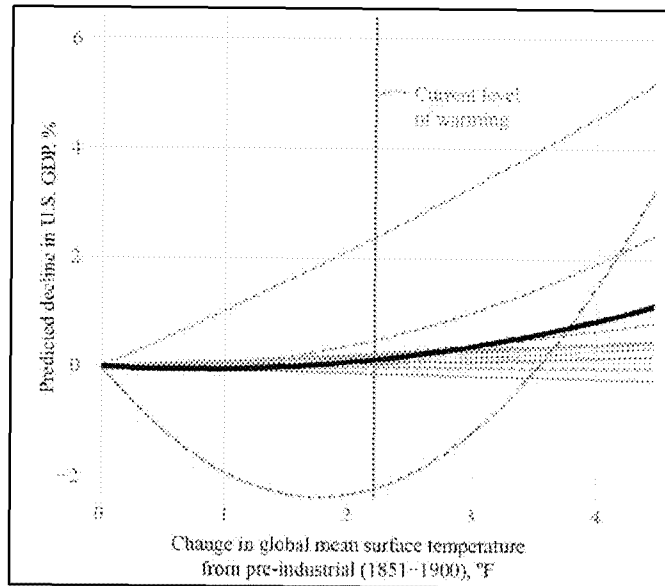


Figure 11.2: Decline in U.S. GDP per degree of warming. Source: CEA-OMB (2023)

The expectation that significant global warming would have a small impact on the U.S. economy was acknowledged quietly by the Biden Administration, even as the President was proclaiming a climate emergency. Figure 11.2, from a 2023 CEA-OMB report, shows the expected decrement in U.S. GDP as a function of temperature rise. The colored lines show the results of a dozen peer-reviewed published studies while the solid black line is their average. The figure could be summarized as “a few percent impact for a few degrees of warming”. Given that the economy’s annual growth rate is expected to be 1-2 percent, the impact of a warming globe on the U.S. GDP is indeed negligible.

11.2 Models of the Social Cost of Carbon

The Social Cost of Carbon (SCC) is a tool for quantifying the economic impact of carbon dioxide emissions, helping policymakers weigh the costs and benefits of climate policies. It estimates the damage caused by emitting one additional ton of CO₂, expressed in dollars. More formally, the SCC is the discounted present value of the current and future marginal loss of economic welfare due to an additional ton of CO₂ entering the atmosphere.

11.2.1 Estimating the SCC

Although the literature refers to “estimates” of the SCC, it is not estimated in the way other economic statistics are estimated. For instance, data on market transactions including prices and quantities can be used to estimate the current inflation rate or the growth rate of per capita real Gross Domestic Product, and there are well-understood uncertainties associated with these quantities. But there are no market data available to measure many, if not most, of the marginal damages or benefits believed to be associated with CO₂ emissions, so these need to be imputed using economic models.

For example, an influential component of some SCC calculations is the perceived social cost associated with a changed risk of future mortality due to extreme weather. There is no market in which people can directly attach a price to that risk. At best economists can try to infer such values by looking at transactions in related markets such as real estate or insurance, but isolating the component of price changes attributable to atmospheric CO₂ levels is very difficult.

Economists use IAMs to compute the SCC. Two of the best known are the Climate Framework for Uncertainty, Negotiation and Distribution (“FUND”, Tol 1997) and Nordhaus’ DICE. IAMs embed a “damage function” or set of functions relating ambient temperature to local economic conditions. The assumptions embedded in the damage function will largely determine the resulting SCC. IAMs also assume a long-term discount rate or, as in DICE, compute the optimal internal discount rate as part of the solution.

One approach to developing a damage function is to begin with estimates of the costs (or benefits) of warming in specific sectors in countries around the world and aggregate up to a global amount. This was the approach used in FUND. An alternative approach is to develop a simple equation that penalizes global income according to a simple quadratic function of the average global temperature. This approach was used in DICE. In the case of the FUND model many hundreds of parameters had to be selected, whereas in DICE only three were needed and were originally chosen to assign a predetermined penalty (1.2%) to global output as of 3°C warming, with a quadratic term implying that damages grow with the square of the global average temperature anomaly. Barrage and Nordhaus (2024) recently changed the parameters to increase the penalty at 3°C to 1.6%, and added a discrete additional 1.0 percent GDP penalty at 3°C warming to account for “tipping points” (discrete large-scale environmental changes triggered by crossing a warming threshold) and a “judgmental adjustment” of 0.5 percent for excluded impacts at 3°C warming. Not surprisingly the newer version of DICE generates much higher SCC estimates than before.

The concepts of estimation and uncertainty do not readily apply to SCC calculations. By comparison, the question of whether precipitation has trended up or down along the South Carolina coast for the past hundred years can be addressed by collecting rainfall data, estimating a trend parameter and calculating statistical confidence intervals using methods with well-understood mathematical properties. In this way uncertainty can, in principle, be resolved by collecting more data and applying more accurate methods. But no amount of data collection can change the fact that many components of the SCC are unknown and rely on judgment and opinion based on knowledge of the underlying literature on the physical effects of climate change.

SCC calculations are thus best thought of as “if-then” statements: *if* the following assumptions hold, *then* the SCC is \$X per tonne. The list of ‘if’ statements includes the premise that the world’s climate and economy work according to the representation in the IAM. One way this might fail to hold is in the timing of warming. Every IAM assumes a value of the Equilibrium Climate Sensitivity (ECS), which controls the amount of warming that results from CO₂ emissions and can be freely varied for the purpose of generating a distribution of SCC values associated with uncertainties over ECS. But as Roe and Baumann (2013) pointed out, time-to-equilibrium increases with the square of ECS, so an upward adjustment of the ECS parameter without an appropriate slowing down of the adjustment process can yield distorted present value damage estimates. In particular, the upper tail of warming associated with some commonly-used ECS distributions is physically impossible for even a thousand years into the future (Roe and Baumann 2013)

yet in an IAM would be realized within a couple of centuries. Failure to align ECS with time-to-equilibrium will lead to an overestimate of the SCC value.

11.2.2 Variations in the SCC

Every level of the IAM calculation includes assumptions, some more influential than others. Key assumptions include the following.

- The discount rate: Climate damages accrue over a long time horizon and costs a century or two in the future need to be discounted to the present. The higher the discount rate the smaller the present value of future damages and vice versa. The discount rate represents the opportunity cost of spending money today rather than investing it and then having more to spend tomorrow. Some economists have argued for the use of very low discount rates in SCC calculations, resulting in policy recommendations that favor relatively large immediate investments in CO₂ emission reductions. The downside is that other investments could potentially earn a larger rate of return for society.
- Equilibrium Climate Sensitivity: IAMs have customarily employed a value of 3.0°C or 3.1°C following the IPCC's guidance. The most recent data-driven ECS values tend to be lower than this (see Chapter 4). Dayaratna *et al.* (2017, 2020, 2023) have shown that use of lower empirically-derived ECS values dramatically lower the resulting SCC estimate, even when low discount rates are used.
- Damage function coefficients: IAMs assume CO₂ and warming cause net harms that increase exponentially with temperature. More recently, IAMs have also incorporated effects from assumed potential climate tipping points. The FUND model took limited but explicit account of CO₂ fertilization effects in agriculture. Since the coefficients were selected prior the publication of the current evidence of global greening and the magnitude of benefits to crops from elevated CO₂ (see Chapters 2 and 9) the growth effects are likely understated. The DICE model (and others) did not explicitly include any CO₂ fertilization benefit, except to the extent it was taken into account in the literature consulted when picking the damage function coefficients. The damage function in FUND contains a region in which low warming yields net benefits in many regions, a finding which is supported by econometric models of warming and growth (Berg *et al.* 2023) and econometric simulations of agricultural changes (McKittrick 2025). The DICE damage function, by construction, rules out net benefits at any warming level.
- Emission scenarios: IAMs generate SCC estimates that increase as the pre-existing concentration of CO₂ increases. Consequently the value of damages later in the century will be higher, depending on the assumed baseline emissions over the coming decades.
- Abatement costs: IAMs represent the cost to the economy of reducing CO₂ emissions. If CO₂ emission reductions are assumed to be inexpensive, then the model will conclude that the optimal policy should aim for deeper emission cuts and vice versa.

It is informative to ascertain whether SCC results are invariant to changes in some assumptions. But when different assumptions result in higher or lower SCC values, the change in the SCC value does not provide *prima facie* evidence about the validity of the assumptions. For example, in 2023 the U.S. Environmental Protection Agency raised its preferred SCC value about 5-fold over the estimates it had issued ten years earlier. This is not because new data had been collected or better mathematical methods had been invented, but because new assumptions had been used, and the validity of those assumptions was a separate question. One was that global agricultural damages were far higher than previously assumed, based on an analysis in Moore *et al.* (2017). But as discussed in Chapter 9, McKittrick (2025) showed that Moore *et al.* (2017) had used a database in which half the CO₂ change observations were missing. When as many of those observations as possible were recovered from underlying sources and the analysis was rerun, the projected crop yield losses disappeared and turned into gains at all warming levels. Hence the portion of the EPA's SCC revision attributable to agricultural yield losses was unwarranted.

11.2.3 Evidence for low SCC

Chapter 2 reviewed evidence on climate change and greening, and Chapter 9 looked at climate change and U.S. agriculture. Evidence shows that CO₂ fertilization has a stronger beneficial effect on agriculture than was known at the time that IAMs like DICE and FUND were parameterized. Haverd *et al.* (2020) found the observed CO₂ fertilization rate has been almost double what had been predicted by crop models. Dayaratna *et al.* (2023) used the updated empirical ECS distribution estimate of Lewis (2022), which assimilates modern instrumental and paleoclimatic temperature records, and allowed for a 30 percent gain in the CO₂ fertilization benefit in the FUND model, and found that, even at a low discount rate of 2.5 percent, the median SCC as of 2050 is only \$18.67, with a 24 percent probability of the true value being negative. At a five percent discount rate the median SCC value is negative until the mid-2040s and at 2050 was only \$0.37 with a 49 percent probability of being negative. Thus, under reasonable assumptions a mainstream IAM using updated scientific inputs yields evidence consistent with the SCC not being significantly greater than zero.

It should also be noted that the SCC is focused on the social costs of CO₂ emissions from fossil fuel use. It does not measure the private marginal benefits to consumers and society from the availability of fossil fuels. Public willingness to pay for fuels of all types indicates the value to society of reliable, abundant fossil energy. Tol (2017) estimates that the private benefit of carbon is large relative to the social cost. This can be illustrated by noting that the price of a gallon of gas indicates the marginal value to the consumer of the fuel. Suppose we assume a relatively high Social Cost of Carbon of, say, \$75 per tonne. Deflated by a MCPF⁴ value of 1.5 that would result in a carbon tax of \$50 per tonne, which equates to about 44 cents per gallon of gas (Lavelle, 2019). A pre-tax price of \$3.00 per gallon would imply the marginal social benefit of the fuel is nearly seven times the marginal social cost.

11.2.4 Tipping points

SCC calculations typically consider gradual impacts of a warming climate, such as slowly-melting glaciers and increasing average temperature. A driver of potentially high values of the Social Cost of Carbon (SCC) is the introduction into models of discrete catastrophic outcomes associated with abrupt changes (Dietz *et al.*, 2021). They are often referred to as “tipping points.”

The term “tipping point” mingles two different physical concepts that pose different research challenges. Many physical systems are inherently stable unless acted upon with sufficient external energy. For example, an ice cap might remain intact over a wide range of temperatures but once the temperature crosses the 0°C threshold it melts. Such discontinuities are ubiquitous in nature and require an external force. Whether the force needs to be large relative to the size of the system depends on the underlying stability of the system.

A different type of tipping point is called a *bifurcation* and arises from the study of the internal dynamics of nonlinear systems (Crawford, 1991). Many systems have been observed to have more than one equilibrium point and can move between them with minimal or no external influence. For example, a weather system might have two different equilibrium states: one calm and one with a tornado. A transition from one to another can happen either with no external force or with a minuscule change, such as a flap of the proverbial butterfly’s wings (Shen *et al.* 2014). The term “tipping point” is sometimes used to mean a bifurcation of this type and implies instability inherent in the system itself, which is not necessarily dependent on outside forces. It depends, instead, on parameters of the system taking values that support the emergence of bifurcations (Crawford, 1991).

The two different concepts imply different research questions. Regarding the first we are interested in whether components of the climate system are susceptible to abrupt discontinuities in response to

⁴ Marginal Cost of Public Funds: the optimal carbon tax rate is the SCC divided by the MCPF (Sandmo 1977).

sufficiently-large anthropogenic forcing. Regarding the second we are interested in whether the Earth’s climate system has inherent bifurcations that imply the possibility of abrupt transitions with or without external forcing.

Models have been developed that imply the second type is a possibility. Kypke *et al.* (2020) presented a simple climate model in which the GHG concentration is one of the parameters that controls the emergence of bifurcations of the Arctic climate to one with both cold and warm equilibria. If sufficiently high GHG forcing combined with a sufficiently high rate of ocean heat transport are imposed a bifurcation becomes possible. More generally GCMs have been observed to contain bifurcations and multiple equilibria (Brunetti and Ragon, 2023).

The possible existence of bifurcations in the Earth’s climate system implies abrupt transitions are possible, not just in response to large forcing but also to small perturbations. This places tipping points into the category of low-likelihood and potentially catastrophic events, such as large meteor strikes. A key question to ask is whether those kinds of tipping points can be predicted. Current research has not resolved that question (Dakos *et al.*, 2024) and indeed might not be able to since one implication of the “butterfly effect” is the existence of predictability boundaries of nonlinear systems (Palmer *et al.*, 2014). It is therefore not obvious how to incorporate such possibilities into SCC calculations. Small variations in assumptions will lead to arbitrarily large variations in the resulting SCC with no grounds for choosing among them. If such tipping points are possible the most appropriate stance for economic policy is to maximize resilience to any form of external catastrophe since it is unlikely we could predict it or prevent it from happening.

AR6 (WGI, Chapter 1) focuses mainly on the first type of tipping point, namely an abrupt change in response to external forcing. This is also the meaning associated with popular usage of the “tipping point” concept in discussions of climate change (see <https://report-2023.global-tipping-points.org/what-is-a-tipping-point/> for example). As summarized by AR6, there is evidence of abrupt change in the paleoclimate record, and some of these events have been interpreted as tipping points. Some projections with Earth System Models for example have produced tipping points such as Amazon forest dieback in response to specified values of CO₂ concentration or temperature increases.

The alarm surrounding climate tipping points is reflected by *The Global Tipping Points Report* that was launched at the COP28 on 6 December 2023 (Lenton *et al.*, 2023). It identifies more than 25 parts of the climate system said to constitute tipping points. What gets classified as a climate “tipping point” is a moving target. The most common examples in the literature and assessment reports include: Greenland ice sheet disintegration, West Antarctic ice sheet disintegration, summertime disappearance of Arctic sea ice, Amazon rainforest dieback, coral reef dieoff, thawing of permafrost and methane hydrates, Atlantic Meridional Overturning Circulation collapse, boreal forest shift, West African monsoon shift, and Indian Monsoon shift.

All such tipping points require a certain amount of system instability in order to exhibit an abrupt transition in response to warming. For this reason there seems to be very little to discriminate between a tipping event and natural climate variability. Natural climate variability has in the past produced shifts in the West African and Indian monsoons, Amazon forest and coral reef dieback, and disintegration of parts of the Greenland and West Antarctic ice sheets. These impacts can reverse on the decadal and century timescales associated with natural climate variability and ecosystem responses.

Some abrupt changes are potentially more consequential, including collapse of the West Antarctic ice sheet and collapse of the Atlantic Meridional Overturning Circulation (AMOC). AR6 WG1 Summary for Policy Makers states:

The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all emission scenarios. While there is *high confidence* in the 21st century decline, there is only *low*

confidence in the magnitude of the trend. There is *medium confidence* that there will not be an abrupt collapse before 2100. (C.3.4)

There is limited evidence for low-likelihood, high-impact outcomes (resulting from ice-sheet instability processes characterized by deep uncertainty and in some cases involving tipping points) that would strongly increase ice loss from the Antarctic Ice Sheet for centuries under high GHG emissions scenarios (e.g., SSP5-8.5). (B.5.2)

For the purpose of SCC calculations, the research question implied by this type of tipping point is whether such events have been observed in the past in climate conditions similar to what we currently experience or will in the near future. AR6 finds little evidence for impending collapse of the Atlantic Meridional Overturning Circulation or the West Antarctic ice sheet. It finds there is no tipping point associated with Arctic Sea ice (AR6 Technical Summary p. 76)

Dietz *et al.* incorporated several potential tipping points (abrupt changes) into an SCC model and found they added about 25 percent to the estimate, mainly associated with thawing permafrost and release of methane hydrates. However, the IPCC considers this scenario *very unlikely* (AR6 Technical Summary p. 107).

In summary, there might be unknown bifurcation tipping points that are associated with natural climate processes, but this possibility does not translate into specific guidance on the SCC. There are potential abrupt change points in the climate system in response to warming, although the IPCC assigns low probabilities to most, including the largest ones. When these have been considered, the result is only a modest increase in the SCC value in the 21st century.

11.2.5 Are there alternatives?

It is increasingly being argued that the SCC is too variable to be useful for policymakers. Cambridge Econometrics (Thoung, 2017) stated it's "time to kill it" due to uncertainties. The UK and EU no longer use SCC for policy appraisal, opting for "target-consistent" carbon pricing (UK Department for Energy Security and Net Zero 2022, Dunne 2017). However, the uncertainty of SCC estimates doesn't mean that other regulatory measures are inherently better or more efficient. Many emissions regulations (such as electric vehicle mandates, renewable energy mandates, energy efficiency regulations and bans on certain types of home appliances) cost far more per tonne of abatement than any mainstream SCC estimate, which is sufficient to establish that they fail a cost-benefit test.

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12 GLOBAL CLIMATE IMPACTS OF U.S. EMISSIONS POLICIES

Chapter Summary

U.S. policy actions are expected to have undetectably small direct impacts on the global climate and any effects will emerge only with long delays.

12.1 The scale problem

The emissions rates and atmospheric concentrations of criteria air contaminants are closely connected because their lifetimes are short and their concentrations are small; when local emissions are reduced the local pollution concentration drops rapidly, usually within a few days. But the global average CO₂ concentration behaves very differently, since emissions mix globally and the global carbon cycle is vast and slow. Any change in local CO₂ emissions today will have only a very small global effect, and only with a long delay.

Following the emission of a pulse (release) of CO₂ into the atmosphere only about 40 ± 15 percent of the extra CO₂ will have been sequestered after twenty years. That fraction rises to 75 ± 10 percent after a thousand years, and the remainder will be gradually removed over the ensuing tens of thousands of years (Ciais *et al.*, 2013, pp. 472-473). Consequently, any reduction in U.S. emissions would only modestly slow, but not prevent, the rise of global CO₂ concentration. And even if global emissions were to stop tomorrow, it would take decades or centuries to see a meaningful reduction in the global CO₂ concentration and hence human influences on the climate.

Reducing the atmospheric stock of CO₂ would require emissions to fall below the natural sequestration rate, assuming the entire increase is anthropogenic. Since that rate has been averaging about 50 percent of emissions in recent decades, a reduction of global emissions by 50 percent would (at least temporarily) halt the rise in atmospheric CO₂. The 1997 Kyoto Protocol proposed to cap industrial nations' CO₂ emissions at a modest five percent below 1990 levels by the year 2012. Even though this policy was too difficult for most nations to implement, full compliance would not have substantially reduced atmospheric CO₂ levels. It would only have slightly slowed CO₂ growth, reaching the projected year 2100 level in 2105 instead (Wigley, 1998). Lomborg (2016) estimated that full compliance with the Paris Accord would not stop warming, it would only prevent about 0.1C warming and delay hitting the baseline year 2100 temperature levels by about a decade.

Thus, in contrast with conventional air pollution control, even drastic local actions will have negligible local effects, and only with a long delay. The practice of referring to unilateral U.S. reductions as “combatting climate change” or “taking action on climate” therefore reflects a profound misunderstanding of the scale of the issue.

12.2 Case study: U.S. motor vehicle emissions

The scale problem can be illustrated with reference to U.S. motor vehicles. The EPA's 2009 Endangerment Finding focused on CO₂ emissions from cars and light-duty trucks in the U.S. because Section 202(a) of Clean Air Act mandates the EPA to set emissions standards for motor vehicles if pollutants are found to endanger public health or welfare. The 2009 Endangerment Finding therefore obligated the EPA to regulate emissions from new motor vehicles, ostensibly to reduce or eliminate climate-related harms to the U.S. public.

Two questions that naturally arise are: (1) How large a reduction in CO₂ emissions would result from such regulation? and (2) What would be the climate impact of such regulation?

The first question can be addressed by comparing U.S. vehicle-based CO₂ emissions to the global total. The second question can be addressed by using the fact that the reduction in global warming would be, according to the models relied upon by the EPA, proportional to the reduction in global emissions, keeping in mind that the change in the CO₂ content of the atmosphere in any given year is the result of total global CO₂ emissions, not just U.S. emissions.

In 2022, the emissions from U.S. cars and light duty trucks totaled 1.05 billion metric tons of carbon dioxide (GtCO₂, EPA 2024). Meanwhile global CO₂ emissions from energy use totaled 34.6 GtCO₂ (Energy Institute 2024). Hence U.S. cars and light trucks account for only 3.0 percent of global energy-related CO₂ emissions. To a first approximation we can say that even eliminating *all* U.S. vehicle-based emissions would retard the accumulation of CO₂ in the atmosphere by a year or two over a century.

It would also reduce the overall warming trend by at most about 3 percent. For the period 1979-2023, which has the most extensive global coverage of a variety of weather data types, warming trends are determined to a precision of about ± 15 percent, so the impact of reducing the rate of global warming by eliminating U.S. vehicle CO₂ emissions would be far below the limits of measurability. Given that global-average temperature is the most direct climate change metric, impacts on any secondary climate metrics (e.g. severe weather, floods, drought, etc.) from reducing U.S. vehicle CO₂ emissions would be even less measurable.

Consequently, in contrast to the case of local air contaminants like particulates and ozone, even the most aggressive regulatory actions on GHG emissions from U.S. vehicles cannot be expected to remediate alleged climate dangers to the U.S. public on any measurable scale.

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GLOSSARY

2XCO2: Doubling of the atmospheric carbon dioxide (CO₂), a commonly used baseline for addressing climate change. In 2025, atmospheric CO₂ concentrations were approximately 50 percent of the way to 2XCO₂ compared to 1800.

ABATEMENT: In the context of environmental policy, the reduction of emissions.

ACE (Accumulated Cyclone Energy): A statistical measure of a tropical cyclone's energy accumulated over its lifetime, calculated from a summation of the square of maximum sustained wind speeds.

ACIDIFICATION: A commonly used term for the reduction in ocean pH from more alkaline to less alkaline values.

ACRIM (Active Cavity Radiometer Irradiance Monitor) GAP: the gap in total solar irradiance data between 1989 and 1991 caused by a delay in the launch of a satellite-borne monitor in time to overlap and intercalibrate with the prior system.

AEROSOLS: Tiny solid or liquid particles suspended in the air.

ALKALINE: Having a chemical pH greater than 7.0. The “opposite” of acidic, which means a pH less than 7.0.

AMBIENT: Relating to the immediate surroundings of something.

AMO: Atlantic Multidecadal Oscillation, a 60-year cycle of sea surface temperatures in the North Atlantic.

ANTHROPOGENIC: Created by humans.

AR (Assessment Reports): Periodic assessments published by the Intergovernmental Panel on Climate Change evaluating current knowledge of the climate system, global change, and associated issues. An AR now consists of reports from three working groups, the first (WG1) concerned with physical science and the others concerned with societal impacts and mitigation strategies. The most recent was AR6.

ATTRIBUTION: Assertion of a causal relation, chiefly from anthropogenic GHG emissions to observed climate patterns.

AUTOCORRELATION: The phenomenon in which the current value of a random time series variable is correlated with its value in a previous time period.

BIOMASS: The total quantity or weight of organic matter in a given area or volume.

CARBON: The 6th element in the periodic table. Popularly used as a shorthand term for carbon dioxide.

CMIP (Coupled Model Intercomparison Project): The Intergovernmental Panel on Climate Change's organized effort to compare many different global ocean-atmosphere climate models when they are all forced with the same emissions scenario(s). The two most recent were the CMIP5 and CMIP6 for, respectively, AR5 and AR6.

CLIMATE CHANGE: A change in climate due to human influences, as opposed to climate variability which is natural in origin.

CONUS: The contiguous 48 U.S. states.

DICE (Dynamic Integrated model of the Climate and Economy): An Integrated Assessment Model developed by William Nordhaus in 1993.

DISCOUNT RATE: The interest rate used to convert future costs and benefits into their present value. Varies inversely with present value so a high discount rate reduces the present value of future costs and benefits.

DRY ICE: Frozen carbon dioxide.

ECONOMETRICS: The branch of economics concerned with the use of statistical methods (chiefly multiple regression) to analyze economic systems.

ECS (Equilibrium Climate Sensitivity): The total amount of eventual global-average surface warming in response to a hypothetical doubling of the atmospheric CO₂ concentration compared to pre-Industrial levels.

EL NIÑO: The warm phase of the El Niño – Southern Oscillation, involving weaker upwelling of cold water off the South American coast and weaker Pacific trade winds.

EMISSIONS SCENARIO: An assumed scenario of future greenhouse gas emissions (or resulting atmospheric concentrations) based upon assumptions regarding global economic activity, the prevalence of fossil fuel use, and (sometimes) global carbon cycle model estimates of the rate of CO₂ uptake by land and ocean.

ENDANGERMENT FINDING (EF): The 2009 finding by the Administrator of the Environmental Protection Agency that emissions of well-mixed greenhouse gases (primarily CO₂) endanger human health and welfare.

ENSO: El Niño – Southern Oscillation, a prominent natural climate fluctuation involving year-to-year variations in the upwelling of cold water off the equatorial coast of South America and associated strengthening or weakening of trade winds across the Pacific Ocean.

FACE: (Free-Air CO₂ Enrichment) Large-scale open-air studies that expose plants to elevated CO₂ levels, simulating future climate scenarios.

FOSSIL FUEL: A natural hydrocarbon fuel such as coal, oil, or natural gas formed in the geological past from the remains of living organisms.

FUND (Framework for Uncertainty, Negotiation, and Distribution): An Integrated Assessment Model developed by Richard Tol in 1997.

GBR (Great Barrier Reef): The world's largest coral reef ecosystem located off the northeast coast of Australia.

GDP (Gross Domestic Product): Total market value of all the final goods and services produced within a country's border, usually over one year.

GHCN (Global Historical Climatology Network): A time-varying number of globally distributed weather stations making hourly, daily, or monthly measurements of precipitation, temperature and sometimes snowfall and snow depth.

GLOBAL GREENING: The satellite-observed increase in greenness in most vegetated land areas observed since the early 1980s.

GNP (Gross National Product): Total market value of all the final goods and services produced by the citizens of a country, including exports and imports, usually over one year.

GDP (Gross National Product): Total market value of all the domestically-produced final goods and services produced by the citizens of a country, usually over one year.

GREENHOUSE EFFECT (GHE): The tendency for any planetary atmosphere containing greenhouse gases to be warmer in the lowest layers than if those gases did not exist.

GREENHOUSE GAS (GHG): An atmospheric gas that absorbs and emits infrared radiation, especially water vapor, CO₂, and methane.

HURST PHENOMENON: See long term persistence.

HYDROLOGY: The study of the movement of water, especially on land and in the atmosphere.

IAM (Integrated Assessment Model): A computerized tool that combines economics, climate science, and social sciences to provide quantitative relationships between human and Earth systems, helping to inform policy decisions.

IEA (International Energy Agency): A Paris-based intergovernmental organization, established in 1974, that provides policy recommendations, analysis and data on the global energy sector.

IPCC (Intergovernmental Panel on Climate Change): A panel of international experts and governmental representatives established by the United Nations and World Meteorological Organization in 1988 to provide governments at all levels with scientific information that they can use to develop climate policies.

IR (Infrared): Heat radiation that all solid objects and greenhouse gases emit by virtue of their temperature.

LA NIÑA: The cool phase of ENSO, involving stronger upwelling of cold water off the South American coast and stronger Pacific trade winds.

LONG TERM PERSISTENCE (LTP, or HURST PHENOMENON): A form of autocorrelation in which random fluctuations induce long term but not permanent changes in the mean value of a series, which shows up in some climate data series as cyclical or trending patterns on short time scales.

MAIZE: Corn.

MODEL: A computer code or collection of codes which quantify our knowledge of various processes and the interactions between those processes.

MORTALITY: Death or number of deaths, usually expressed for a specific population and period.

NCA (National Climate Assessment): A periodic report mandated by the Global Change Research Act of 1990 summarizing the impact of climate change on the United States. There have been five NCA reports: NCA1 (2000), NCA2 (2009), NCA3 (2014), NCA4 (2017-18), and NCA5 (2023).

OECD (Organization for Economic Cooperation and Development): A group of 38 member countries that have a democratic system of government and free economic systems.

PALEOCLIMATE: Climate of the distant past, before modern weather instruments were widely used (typically pre-1850), necessitating the use of “proxy” measurements such as tree rings, ice core, pollen records, etc.

PDI (Power Dissipation Index): A statistical estimate of the accumulated destructive potential of a tropical cyclone over time, calculated as a summation of the cube of the maximum sustained wind speeds.

PDO: Pacific Decadal Oscillation, a recurring ocean-atmosphere interaction centered over the Pacific basin associated with predominantly warm or cool patterns that influence the global climate.

PHOTOSYNTHESIS: The process by which plants grow, requiring carbon dioxide, water, and light at sufficiently warm temperatures (10 to 35 deg. C for optimal function).

PPM: Parts per million, a measure of the concentration of a substance in (for example) the atmosphere

PRE-INDUSTRIAL: The near-term historical period before which human greenhouse gas emissions were considered significant, usually assumed to be the mid-1700s.

RADIATIVE FEEDBACK: A change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in surface temperature.

RADIATIVE FORCING: The change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in greenhouse gases, anthropogenic aerosols, volcanoes, etc.

RCP (Representative Concentration Pathway) SCENARIOS: Different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Fifth Assessment Report (AR5). RCP scenarios have a number label (e.g. RCP6.0) indicating how much radiative forcing they assume in 2100 relative to pre-Industrial times, in Watts per square meter. RCP4.5 and RCP6.0 are intermediate scenarios, whereas RCP8.5 is an extreme scenario with very large future emissions of greenhouse gases.

REGRESSION: A statistical method for selecting the coefficients of a linear equation to explain the behaviour of a dependent variable in terms of variations in one or more explanatory variables.

RICARDIAN ANALYSIS: A method used in environmental economics named after David Ricardo to estimate the economic impacts of climate change, particularly on agriculture, by making use of the hypothesis that expected changes in the return to future agricultural activity will be capitalized into current land values.

SCC (Social Cost of Carbon): An estimate of the net economic damages, measured in present-value dollars, caused by emitting one additional ton of CO₂ into the atmosphere.

SSP (Shared Socioeconomic Pathway) SCENARIOS: Different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Sixth Assessment Report (AR6). Some of the SSP scenarios are analogous to the older RCP scenarios, for purposes of continuity and comparison to earlier climate model assessments.

TC: Tropical cyclone.

TMAX: The daily maximum surface air temperature.

TMIN: The daily minimum surface air temperature.

TOA: Top of atmosphere.

TONNE: Metric ton.

TOXICOLOGY: The study of the adverse effects of chemical substances on living organisms.

TREND: A coefficient, usually estimated using linear regression, representing the slope of a line of best fit through a time series of data, indicating any tendency for the series mean to move up or down over time.

TSI (Total Solar Irradiance): The measure of the total amount of incident solar radiation per unit area, including all wavelengths of electromagnetic radiation, that reaches the Earth's atmosphere. Typically shown in units of watts per square meter (W/m²).

UHI (Urban Heat Island): The tendency for inhabited areas to be warmer than their rural surroundings, due to the replacement of natural land and vegetation with roads, parking lots, buildings, and waste heat sources.

USHCN: The U.S. Historical Climatology Network, consisting of quality-controlled temperature and precipitation data from 1,218 surface weather stations.

METADATA FOR FIGURES AND TABLES

Figure 2.1 Screen shot from Figure 3 of Zhu *et al.* 2016 <https://www.nature.com/articles/nclimate3004>

Figure 2.2 Data replotted from Berner 2006 Figure 18, with annotation in red added by authors
<https://www.sciencedirect.com/science/article/pii/S0016703706002031>

Figure 2.3 Screen shot from Gerhart and Ward (2010) Figure 2
<https://nph.onlinelibrary.wiley.com/doi/pdf/10.1111/j.1469-8137.2010.03441.x>

Figure 2.4 Screenshot from Copernicus Marine Services
https://data.marine.copernicus.eu/product/GLOBAL_OMI_HEALTH_carbon_ph_area_averaged/description

Figure 2.5 Screen shot from AIMS (2023) Figures 2-4
https://www.aims.gov.au/sites/default/files/2022-08/AIMS_LTMP_Report_on%20GBR_coral_status_2021_2022_040822F3.pdf

Figure 3.1.1 Screen shot of AR6 WG1 Ch2 Fig 10

Figure 3.1.2 Screen shot of AR6 WG1 Ch7 Fig 7-6

Figure 3.1.3 Author created figure. CO2 data source: <https://gml.noaa.gov/ccgg/trends/index.html>

Figure 3.2.1 Screen shot from Hausfather *et al.* (2019) Figure S4 <https://doi.org/10.1029/2019GL085378>

Figure 3.2.2 Author created figure. Data source: Freidlingstein *et al.* (2024)
<https://essd.copernicus.org/preprints/essd-2024-519>
Data source: <https://globalcarbonbudget.org/download/1442/>

Figure 3.2.3 Author-created using OLS trends, Data source:
<https://globalcarbonbudget.org/download/1442/>

Figure 3.2.4 Author-created using OLS trends, Data source:
<https://globalcarbonbudget.org/download/1442/>

Figure 4.1 Screen shot from Scafetta (2021) Figure 1 <https://doi.org/10.3390/cli9110161>

Figure 5.1 Data source: <https://climexp.knmi.nl/start.cgi>. Author-created figure. One ensemble member per model, yearly average temperatures are computed from the global monthly raw temperatures; ‘range’ is the warmest model temperature minus the coolest model temperature in each year; standard deviation computed across all 33 models’ raw temperatures in each year.

Figure 5.2 Screen shot from Scafetta (2023) Figure 2
<https://doi.org/10.1007/s00382-022-06493-w>

Figure 5.3 Author created figure. Data source: <https://climexp.knmi.nl/start.cgi>. One SSP370 ensemble member per model. Linear OLS trends computed from global monthly temperature anomalies relative to 1981-2010.

Figure 5.4 Author created figure, based on Figure 3 of McKittrick and Christy (2020)

<https://doi.org/10.1029/2020EA001281>. Updated using same methods and data extended from 2014 to 2024, see McKittrick and Christy (2025) in chapter references.

Figure 5.6 Screen shot of IPCC AR5 Figure 10.SM1, with author annotations

Figure 5.7 Author created figure following Christy and McNider (2017) <https://doi.org/10.1007/s13143-017-0070-z> with updated data available at https://www.nsstc.uah.edu/data/cmip6/ERA5_REANALYSES/ and https://www.nsstc.uah.edu/data/cmip6/JRA3Q_REANALYSES/ compiled here https://www.nsstc.uah.edu/data/cmip6/CWG25_Fig_5.7_Table_250627.xlsx

Figure 5.8 Screen shot from https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhland&ui_season=1 (accessed May 27, 2025)

Figure 5.9 Screen shot from Rugenstein and Hakuba (2023) Figure 1 <https://doi.org/10.1029/2022GL101802>

Figure 5.10 Author created figure. Data source <https://climexp.knmi.nl/start.cgi>. OLS linear trends. One SSP370 ensemble member per model, averaged surface air temperatures for June through August over 31N to 49N latitude, 84W to 102W longitude. Observed temperature data for same months from NOAA/NCEI at <https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/statewide/time-series> for the 12 Corn Belt states averaged together.

Figure 6.1.1 Author replot of Figure 10 from Koutsoyiannis (2013) <http://dx.doi.org/10.1080/02626667.2013.804626>

Figure 6.2.1 Screen shot of figure from Maue (2025) <https://climatlas.com/tropical/>

Figure 6.2.2 Author created figure. Data from National Hurricane Center (2024) <https://www.nhc.noaa.gov/climo/>

Figure 6.2.3 Author created figure. Data from NOAA HRD https://www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html

Table 6.2.1 Author created table. Data from NOAA HRD https://www.aoml.noaa.gov/hrd/hurdat/most_intense.html

Figure 6.3.1 Screen shot from NCA4 Figure 6.4

Figure 6.3.2 Author created figure. Data source: https://www.nsstc.uah.edu/data/ushcn_jrc/

Figure 6.3.3 Author created figure. Data source: https://www.nsstc.uah.edu/data/ushcn_jrc/

Figure 6.3.4 Author created figure. Data source: https://www.nsstc.uah.edu/data/ushcn_jrc/

Figure 6.3.5 Author created figure Data source: https://www.nsstc.uah.edu/data/ushcn_jrc/

Figure 6.3.6 Author created figure. Data source: https://www.nsstc.uah.edu/data/ushcn_jrc/

Figure 6.3.7 Screen shot from <https://www.globalchange.gov/indicators/heat-waves>

Box tables. Author created table. Data from McKittrick and Christy (2025)

Figure 6.4.1 Author created figure. Data from McKittrick and Christy (2025)

Figure 6.4.2 Author created figure. Data from McKittrick and Christy (2025)

Figure 6.4.3 Author created figure. Data from McKittrick and Christy (2025)

Figure 6.4.4 Author created figure. Data from McKittrick and Christy (2025)

Figure 6.4.5 Author created figure. Data from McKittrick and Christy (2025)

Figure 6.5.1 Author created figure. Data source: https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv

Figure 6.7.1 Author created figure. Data source: <https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0> accessed June 16, 2025. OLS trend line added.

Figure 6.8.1 Screen shot from Lizundia-Loiola *et al.* (2021) Figure 12.

Figure 6.8.2 Screenshot from Marlon *et al.* (2012) Figure 2 panel C.
<https://www.pnas.org/doi/pdf/10.1073/pnas.1112839109>

Figure 6.8.3 Author created Figure. Data 1926 to 2016:
https://web.archive.org/web/20200212033452/https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html
. Post-2017 <https://www.nifc.gov/fire-information/statistics/wildfires> Accessed June 16, 2025.

Figure 7.1 Screenshot from <https://tidesandcurrents.noaa.gov/sltrends/>

Table 7.1 Author created table. From Section 6.2 of
<https://judithcurry.com/wp-content/uploads/2018/11/special-report-sea-level-rise-3.pdf>

Figure 7.2 Screenshot from https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290
(downloaded 4/22/25)

Figure 7.3 Screenshot from
https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8771450 (downloaded 4/22/2025)

Figure 7.4 Screenshot from
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Figure 7.5 Screenshot from
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Figure 7.6 Author created figure. Data from
https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750

Figure 8.1 Screenshot from
<https://crudata.uea.ac.uk/cru/data/temperature/HadCRUT5.0Analysis.pdf>

Figure 8.2 Screenshot from Hansen and Karecha (2025) Figure 1
<https://www.columbia.edu/~jeh1/mailings/2025/CloudFeedback.13May2025.pdf>

Table 8.1 Screenshot of column 1 of Table 12.12 IPCC AR6 Working Group I report

Figure 9.1 Screenshot From Taylor and Schlenker (2021) Figure 1
<https://www.nber.org/papers/w29320>

Figure 9.2 Screenshot from McKittrick (2025) Figure 1
<https://www.nature.com/articles/s41598-025-90254-2>

Figure 10.1 Screenshot from Pielke (2024) <https://www.nature.com/articles/s44304-024-00011-0> Figure 3.

Figure 10.2 Screenshot from Gasparini *et al.* (2015) Figure 2
[http://dx.doi.org/10.1016/S0140-6736\(14\)62114-0](http://dx.doi.org/10.1016/S0140-6736(14)62114-0)

Figure 11.1 Screen shot from Pielke Jr (2023)
<https://rogerpielkejr.substack.com/p/global-disaster-losses1990-2023>

Figure 11.2 Screenshot from CEA-OMB (2023) <https://bidenwhitehouse.archives.gov/wp-content/uploads/2023/03/CEA-OMB-White-Paper.pdf> Figure 1.

ABOUT THE AUTHORS

John Christy, Ph.D. is the Distinguished Professor of Atmospheric and Earth Sciences and Alabama's State Climatologist at the University of Alabama in Huntsville. He has a B.A. (Mathematics) from CSU Fresno and an M.S. and Ph.D. (Atmospheric Sciences) from the University of Illinois in Urbana-Champaign. He is a Fellow of the American Meteorological Society and recipient of The NASA Medal for Exceptional Scientific Achievement for constructing, with Dr. Roy Spencer, the first global atmospheric temperature dataset from polar orbiting satellites. He served as Lead Author of the 3rd IPCC Assessment Report (2001), he coauthored the National Academy of Science expert report on Surface Temperature Reconstructions (2006), and he has served on the NOAA Climate Change Science Program, NASA's Earth Science Subcommittee, the National Research Council Space Studies Board and the EPA Science Advisory Board. In addition, Dr. Christy has given testimony in 20 Congressional Hearings.

Judith Curry, Ph.D. is Professor Emerita at the Georgia Institute of Technology, where she served as Chair of Earth and Atmospheric Sciences for 13 years. She is President and co-founder of Climate Forecast Applications Network (CFAN). Curry has a PhD in Geophysical Sciences from the University of Chicago. She has authored or coauthored 192 peer-reviewed papers in atmospheric and climate sciences, two textbooks, and most recently the book *Climate Uncertainty and Risk*. Curry is a Fellow of the American Meteorological Society, the American Association for the Advancement of Science, American Geophysical Union, and a Member of the American Academy of Sciences and Letters. She has served on several Science Steering Committees of the World Climate Research Program and also the DOE Biological & Environmental Research Advisory Committee, Earth Science Subcommittee of the NASA Advisory Council, and the NRC Space Studies Board and Climate Research Committee. Dr. Curry has given testimony in 13 Congressional Hearings..

The Honorable Steven E. Koonin, Ph.D. is the Edward Teller Senior Fellow at Stanford's Hoover Institution. He has served as Under Secretary for Science at the Department of Energy (2009-2011), as Chief Scientist for British Petroleum (2004-2009), and as a professor at Caltech (1975 – 2004, the last nine years as Vice President and Provost). Koonin is a member of the National Academy of Sciences and the JASON group of government advisors, as well as a Governor of Lawrence Livermore National Laboratory, having served in similar capacities for the Los Alamos, Sandia, Brookhaven, and Argonne National Laboratories. Other prior roles include a University Professor at New York University, a non-resident Senior Fellow at the American Enterprise Institute, and a Trustee of the Institute for Defense Analyses. Koonin has a BS in Physics from Caltech and a PhD in Theoretical Physics from Massachusetts Institute of Technology. He authored the 2021 bestseller *Unsettled: What Climate Science Tells Us, What It Doesn't, and Why It Matters*, the 1985 textbook *Computational Physics*, and some 200 peer-reviewed papers in physics and astrophysics, scientific computation, energy technology and policy, and climate science.

Ross McKittrick, Ph.D., is a Professor of Environmental Economics at the University of Guelph in Ontario, Canada. He holds a BA in economics from Queen's University, and an MA and Ph.D. in economics from the University of British Columbia. He has published widely in both economics and physical science journals on topics related to climate change, pollution and public policy. His book *Economic Analysis of Environmental Policy* was published by the University of Toronto Press in 2010. His background in applied statistics has led him to author or coauthor peer-reviewed publications across a wide range of topics in the physical sciences including paleoclimate reconstruction, malaria transmission, surface temperature measurement, climate attribution methodology and climate model evaluation. Professor McKittrick has made many invited academic presentations around the world, was an invited contributor to the 2006

National Academy of Sciences report on Surface Temperature Reconstructions, has served as an expert reviewer for the last three IPCC Assessment Reports (Working Groups I and II) and has testified before the U.S. Congress and committees of the Canadian House of Commons and Senate.

Roy W. Spencer, Ph.D., is a Principal Research Scientist at the University of Alabama in Huntsville. He holds a BS in Atmospheric and Oceanic Science from the University of Michigan, and MS and PhD in Meteorology from the University of Wisconsin -Madison. Spencer's published research has focused on monitoring of weather processes and climate change from Earth-orbiting satellites, as well as using simple physical models for diagnosing climate sensitivity and climate feedbacks. As a NASA Senior Scientist for Climate Studies he served as the U.S. Science Team Leader for the Advanced Microwave Scanning Radiometer (AMSR-E) flying on the Aqua satellite, providing our most accurate global measurements of sea surface temperatures, sea ice, and several other features of the climate system. Along with Dr. John Christy, Spencer developed the first satellite-based technique for global temperature monitoring, for which they received NASA's Exceptional Scientific Achievement Medal and the American Meteorological Society's Special Award.



Impacts of Carbon Dioxide Emissions on the U.S. Climate

Climate Working Group
United States Department of Energy
July 15, 2025

Impacts of Carbon Dioxide Emissions on the U.S. Climate

Report to U.S. Energy Secretary Christopher Wright

July 15, 2025

Climate Working Group:

John Christy, Ph.D.

Judith Curry, Ph.D.

Steven Koonin, Ph.D.

Ross McKittrick, Ph.D.

Roy Spencer, Ph.D.

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SECRETARY'S FOREWORD

Energy, Integrity, and the Power of Human Potential

Over my lifetime, I've had the privilege of working as an energy entrepreneur across a range of fields—nuclear, geothermal, natural gas, and more—and I now serve as Secretary of Energy under President Donald Trump. But above all, I'm a physical scientist who sees modern energy as nothing short of miraculous. It powers every aspect of modern life, drives every industry, and has made America an energy powerhouse with the ability to fuel global progress.

The rise of human flourishing over the past two centuries is a story worth celebrating. Yet we are told—relentlessly—that the very energy systems that enabled this progress now pose an existential threat. Hydrocarbon-based fuels, the argument goes, must be rapidly abandoned or else we risk planetary ruin.

That view demands scrutiny. That's why I commissioned this report: to encourage a more thoughtful and science-based conversation about climate change and energy. With my technical background, I've reviewed reports from the Intergovernmental Panel on Climate Change, the U.S. government's assessments, and the academic literature. I've also engaged with many climate scientists, including the authors of this report.

What I've found is that media coverage often distorts the science. Many people—even well-meaning ones—walk away with a view of climate change that is exaggerated or incomplete. To provide clarity, I asked a diverse team of independent experts to summarize the current state of climate science, with a focus on how it relates to the United States.

I didn't select these authors because we always agree—far from it. In fact, they may not always agree with each other. But I chose them for their rigor, honesty, and willingness to elevate the debate. I exerted no control over their conclusions. What you'll read are their words, drawn from the best available data and scientific assessments.

I've reviewed the report carefully and challenged its findings. I believe it faithfully represents the state of climate science today. Still, many readers may be surprised by its conclusions—which differ in important ways from the mainstream narrative. That's a sign of how far the public conversation has drifted from the science itself.

To correct course, we need open, respectful, and informed debate. That's why I'm inviting public comment on this report. Honest scrutiny and scientific transparency should be at the heart of our policymaking.

Climate change is real, and it deserves attention. But it is not the greatest threat facing humanity. That distinction belongs to global energy poverty. As someone who values data, I know that improving the human condition depends on expanding access to reliable, affordable energy. Climate change is a challenge—not a catastrophe. But misguided policies based on fear rather than facts could truly endanger human well-being.

We stand at the threshold of a new era of energy leadership. If we empower innovation rather than restrain it, America can lead the world in providing cleaner, more abundant energy—lifting billions out of poverty, strengthening our economy, and improving our environment along the way.

EXECUTIVE SUMMARY

This report reviews scientific certainties and uncertainties in how anthropogenic carbon dioxide (CO₂) emissions have affected, or will affect, the Nation's climate, extreme weather events, and selected metrics of societal well-being. Those emissions are increasing the concentration of CO₂ in the atmosphere through a complex and variable carbon cycle, where some portion of the additional CO₂ persists in the atmosphere for centuries.

Elevated concentrations of CO₂ directly enhance plant growth, globally “greening” the planet and increasing agricultural productivity. They also make the oceans less alkaline (lower the pH) by an amount within the range of natural variability. That is possibly detrimental to coral reefs, although the recent rebound of the Great Barrier Reef suggests otherwise.

Carbon dioxide also acts as a greenhouse gas, exerting a warming influence on climate and weather. Scenarios of future CO₂ emissions have tended to overestimate observed levels.

The world's several dozen detailed climate models offer little guidance on how the climate responds to elevated CO₂, with the average surface warming under a doubling of the CO₂ concentration ranging from 1.8°C to 5.7°C, a larger range than data driven estimates that suggest a response in the range 1.8°C to 2.7°C.

Detailed climate models generally run “hot” in their description of the climate of the past few decades - too much warming at the surface and too much amplification of warming in the lower- and mid-troposphere. They also produce too much stratospheric cooling, too much snow loss, and too much warming in the U.S. Corn Belt. The combination of overly sensitive models and extreme scenarios for future emissions has exaggerated projections of future warming.

Most extreme weather events do not show long-term trends. Claims of increased frequency or intensity of hurricanes, tornadoes, floods, and droughts are not supported by historical data. Additionally, forest management practices are often overlooked in assessing wildfire activity. Global sea level has risen approximately 8 inches since 1900, but there are significant regional variations in tide gauge data driven primarily by local land subsidence; U.S. tide gauge measurements in aggregate show no obvious acceleration in sea level rise beyond the historical average rate.

The attribution of particular climate changes or extreme weather events to human CO₂ emissions is challenged by natural climate variability, data limitations, and inherent model deficiencies. Moreover, solar activity's contribution to the late 20th century warming might be underestimated.

Both models and experience suggest that CO₂-induced warming might be less damaging economically than commonly believed, and excessively aggressive mitigation policies could prove more detrimental than beneficial. Social Cost of Carbon estimates, which attempt to quantify the economic damage of CO₂ emissions, are highly sensitive to their underlying assumptions and so provide limited independent information.

The report supports a more nuanced and evidence-based approach for informing climate policy. The risks and benefits of a climate changing under both natural and human influences must be weighed against the costs, efficacy, and collateral impacts of any “climate action”, considering the nation's need for reliable and affordable energy with minimal local pollution. Beyond continuing precise, un-interrupted observations of the global climate system, it will be important to make realistic assumptions about future emissions, re-evaluate climate models to address biases and uncertainties, and clearly acknowledge the limitations of extreme event attribution studies. An approach that acknowledges both the potential risks and benefits of CO₂, rather than relying on flawed models and extreme scenarios, is essential for informed and effective decision-making.

PREFACE

This document originated in late March 2025 when Secretary Wright assembled an independent group to write a report on issues in climate science relevant for energy policymaking, with particular focus on the question of whether carbon dioxide emissions endanger the U.S. public. We agreed to undertake the work on the condition that there would be no editorial oversight by the Secretary, the Department of Energy, or any other government personnel. This condition has been honored throughout the process and the writing team has worked with full independence.

The group began working in early April with a deadline of May 28. The short timeline and the technical nature of the material meant that we could not comprehensively review all topics. Rather, we chose to focus on topics that are treated by a serious, established academic literature; that are relevant to our charge; that are downplayed in, or absent from, recent assessment reports; and that are within our competence.

While the report is intended to be accessible to non-experts, we have omitted some introductory or explanatory material that can easily be accessed elsewhere. Nor have we attempted to survey entire literatures related to the topics covered. We have focused as much as possible on literature published since 2020 and referenced previous IPCC and NCA assessment reports. We have also used data through 2024 where possible.

The writing team is grateful to Secretary Wright for the opportunity to prepare this report and for his support of independent scientific assessment and open scientific debate.

John Christy, Ph.D.

Judith Curry, Ph.D.

Steven Koonin, Ph.D.

Ross McKittrick, Ph.D.

Roy Spencer, Ph.D.

PART I: DIRECT HUMAN INFLUENCE ON ECOSYSTEMS AND THE CLIMATE

1 CARBON DIOXIDE AS A POLLUTANT

Chapter summary:

Carbon dioxide (CO₂) differs in many ways from the so-called Criteria Air Pollutants. It does not affect local air quality and has no human toxicological implications at ambient levels. It is an issue of concern because of its potential effects on the global climate, a complex issue that occupies much of this report.

The Clean Air Act of 1970 defined six so-called Criteria Air Contaminants subject to regulation (EPA): particulate matter, ground-level ozone, sulfur dioxide, nitrogen dioxide, lead, and carbon monoxide. In 2007, the Supreme Court ruled that greenhouse gases (CO₂ among them) were also “pollutants” subject to regulation under Clean Air Act (Mass. v. EPA, 2007). While the definition of “pollutant” is ultimately a legal matter, there are important scientific distinctions between CO₂ and the Criteria Air Contaminants. The latter are subject to regulatory control because they cause local problems depending on concentrations that include nuisances (odor, visibility), damage to plants, and, at high enough exposure levels, toxicological effects in humans. In contrast, CO₂ is odorless, does not affect visibility and has no toxicological effects at ambient levels. It is a naturally occurring part of the atmosphere and a key component of human and plant respiration. CO₂ is essential for plant photosynthesis and higher levels are beneficial for vegetation. In these aspects, CO₂ is similar to water vapor.

Ambient outdoor air today contains about 430 parts per million (ppm) CO₂, increasing at about 2 ppm per year. The U.S. Occupational Safety and Health Administration issues guidelines for indoor workplaces in which elevated CO₂ might be encountered, such as where dry ice is used. The Permissible Exposure Limit is 5,000 ppm over 8 hours (OSHA, 2024). Allen *et al.* (2015) reported evidence of diminished performance on some cognitive tasks among workers in office cubicles when exposed to CO₂ levels above 1,000-1,500 ppm. These levels are far larger than any plausible ambient outdoor value through the end of the 22nd century.

The growing amount of CO₂ in the atmosphere directly influences the earth system by promoting plant growth (global greening), thereby enhancing agricultural yields, and by neutralizing ocean alkalinity. But the primary concern about CO₂ is its role as a greenhouse gas (GHG) that alters the earth’s energy balance. How the climate will respond to that influence is a complex question that will occupy much of this report.

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2 DIRECT IMPACTS OF CO₂ ON THE ENVIRONMENT

Chapter summary:

CO₂ enhances photosynthesis and improves plant water use efficiency, thereby promoting plant growth. Global greening due to increased CO₂ levels in the atmosphere is well-established on all continents.

CO₂ absorption in sea water makes the oceans less alkaline. The recent decline in pH is within the range of natural variability on millennial time scales. Most ocean life evolved when the oceans were mildly acidic. Decreasing pH might adversely affect corals, although the Australian Great Barrier Reef has shown considerable growth in recent years.

2.1 CO₂ and global greening

The growing CO₂ concentration in the atmosphere has the important positive effect of promoting plant growth by enhancing photosynthesis and improving water use efficiency. That is evident in the “global greening” phenomenon discussed below, as well as in the improving agricultural yields discussed in Chapter 10.

2.1.1 Measurement of global greening

“Greening” refers to an increase in the fraction of the Earth’s surface covered by plants. It can be quantified by the “Leaf Area Index” (LAI) measured by satellite. Many studies over the past decade have confirmed a global greening pattern (increase in LAI) attributable to rising CO₂ levels. Zhu *et al.* (2016) was one of the first studies to report that global greening was detectable using satellite sensors. From 1982 to 2011 they detected greening over 25-50 percent of the Earth versus “browning” over only four percent and attributed 70 percent of the greening to rising CO₂ levels (see Figure 2.1).

Zheng *et al.* (2017) confirmed the pattern, noting that greening over thirty years had added 8 percent to global leaf area and that greening was mitigating warming. Greening has been observed globally but Chen *et al.* (2019) noted that China and India were exploiting it through land management changes. Thus, while China accounts for only 6.6 percent of global vegetated area it accounts for 25 percent of global net increase in LAI. Piao *et al.* (2020) noted that greening was even observable in the Arctic.

While plant models predict increased photosynthesis in response to rising CO₂, Haverd *et al.* (2020) reported a CO₂ fertilization rate nearly double model predictions. That is, CO₂ fertilization had driven an increase in observed global photosynthesis by 30 percent since 1900, versus 17 percent predicted by plant models. This indicates that global models of the socioeconomic impacts of rising CO₂ have likely understated the benefits to crops and agriculture. The connection between CO₂ fertilization and agriculture will be discussed in Chapter 9.

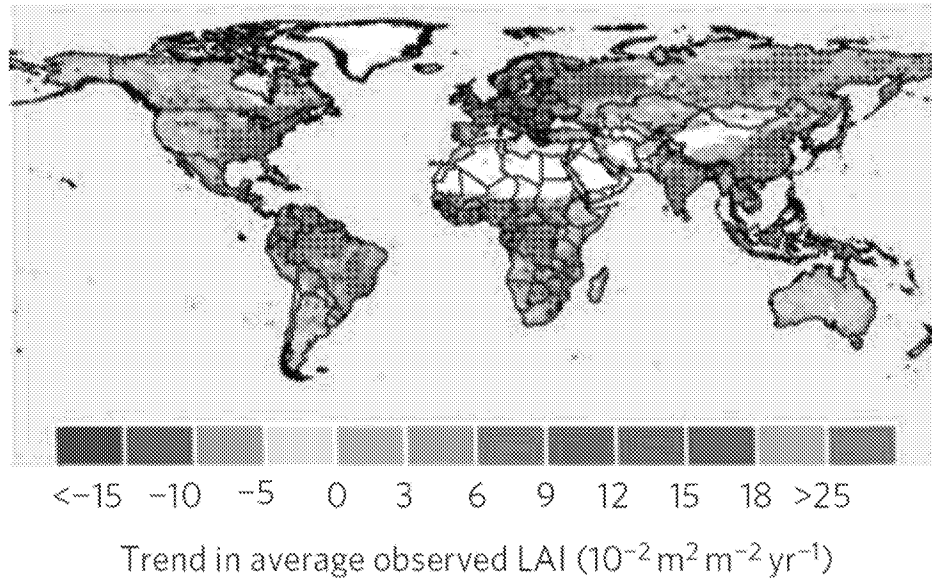


Figure 2.1: Trends in average Leaf Area Index (LAI). Source: Zhu *et al.* 2016 Figure 3.

Finally, Chen *et al.* (2024) surveyed claims that greening had slowed since 2000 due to drought stress. They found instead that faulty satellite sensors were the cause and that the corrected data showed accelerated greening over 55 percent of the globe while browning was accelerating over only 7 percent. In other words, the greening trend continued with no evidence of slowdown, and CO_2 fertilization remained the dominant driver

2.1.2 Photosynthesis and CO_2 levels

Plants build biomass through *photosynthesis*, a process that converts carbon dioxide, water, and light into sugar. The plant enzyme responsible for photosynthesis is Ribulose-1,5-bisphosphate-carboxylase/oxygenase or “Rubisco”. Photosynthesis is initiated when CO_2 is available at the surface of the Rubisco enzyme where it is converted to a molecule with 3 carbon atoms and thereafter incorporated into plant mass. This is referred to as the “C3” process.

Rubisco is estimated to have evolved about 3 billion years ago. Over geological time the Earth’s atmospheric CO_2 levels were usually many times higher than they are today, as shown in Figure 2.2.

About 400 million years ago CO_2 levels were an estimated 2,000-4,000 ppm and were at or above 1,000 ppm for much of the interval from 200 to 50 million years ago (Berner 2006, Judd *et al.* 2024). Over the past 35 million years the level of atmospheric CO_2 has been steadily declining, falling to as low as 170 ppm during glaciations (Gerhart and Ward 2010).

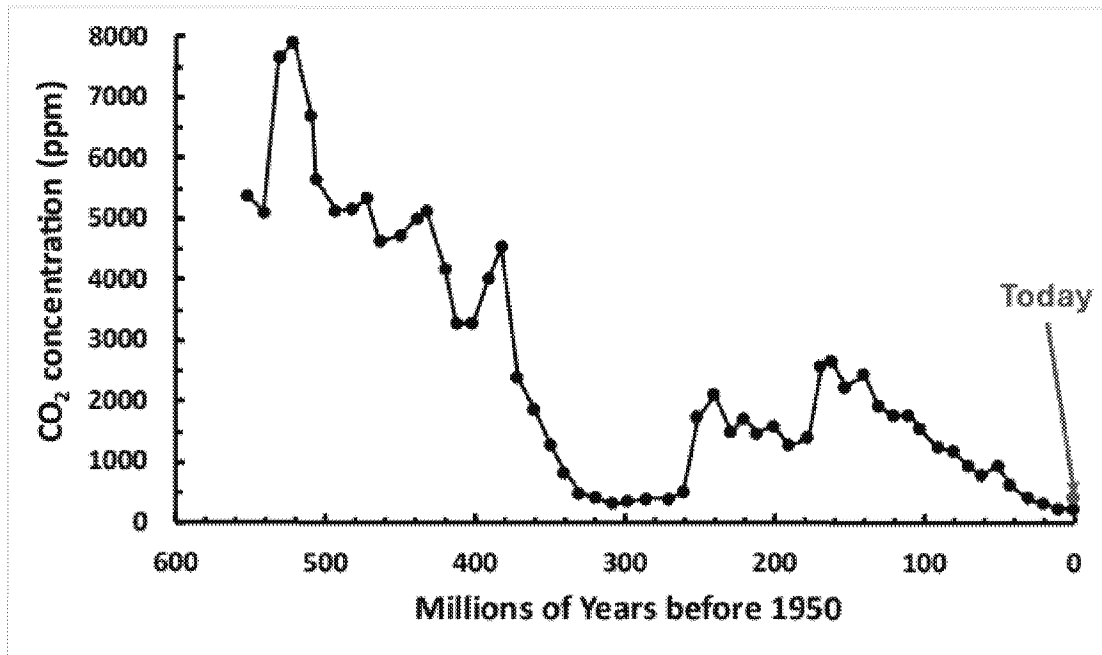


Figure 2.2. Ambient CO₂ levels over the past 550 million years. Today's concentration of 430 ppm is also shown. Source: (Berner 2006)

In response to low-CO₂ conditions some plants evolved another photosynthetic pathway called C₄, in which CO₂ is concentrated in the vicinity of Rubisco, allowing for the C₃ process to function more efficiently. For agricultural purposes the plant categories are:

- C₃: rice, wheat, soybeans and most other crops
- C₄: maize (corn), sugar cane, millet, sorghum

Had atmospheric CO₂ levels continued declining, plant growth would have declined and eventually ceased. Below 180 ppm, the growth rates of many C₃ species are reduced 40-60 percent relative to 350 ppm (Gerhart and Ward 2010) and growth has stopped altogether under experimental conditions of 60—140 ppm CO₂. Some C₄ plants are still able to grow at levels even as low as 10 ppm, albeit very slowly (Gerhart and Ward 2010).

Current CO₂ levels are about 430 ppm, up from 280 ppm in the early 1800s. The positive response of plants to extra CO₂ is illustrated in Figure 2.3, reproduced from Gerhart and Ward (2010). It shows the growth effect of CO₂ on Velvetleaf (*Abutilon theophrasti*) seedlings over 14 days under controlled conditions where only the CO₂ exposure is varied. The gains induced by increasing CO₂ from 150 ppm to 350 ppm continue under a further doubling to 700 ppm.

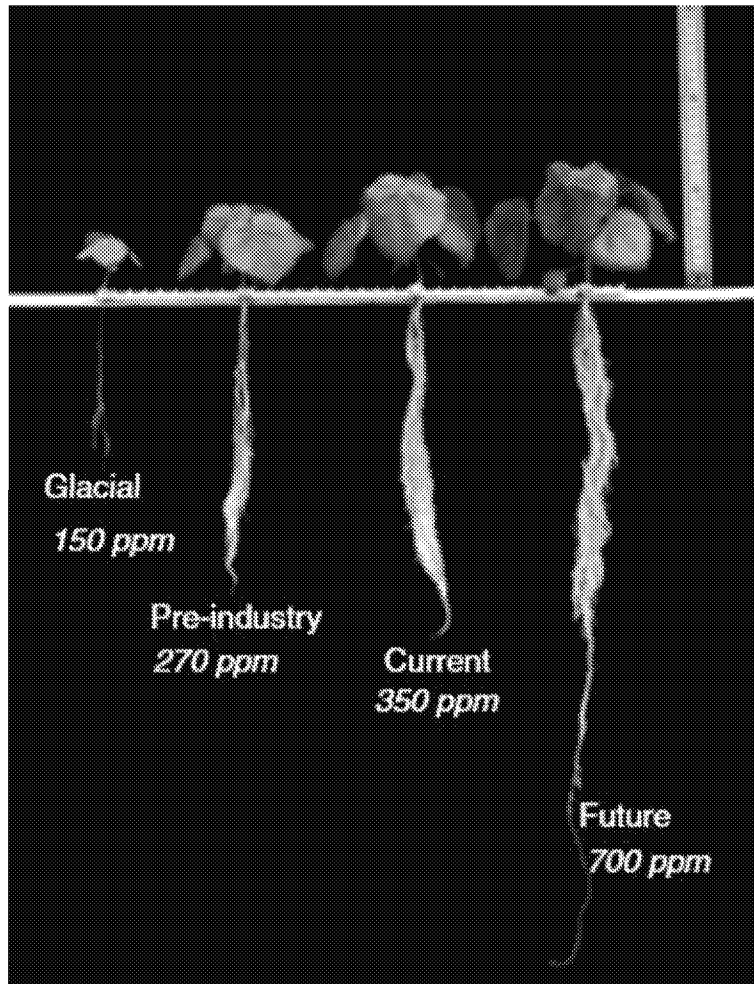


Figure 2.3: growth of *Abutilon theophrasti* after 14 days under identical conditions but for the indicated variations in CO₂ levels. Source: Gerhart and Ward (2010). Note “Current” corresponds to 1988 in image.

Over the past 60+ years there have been thousands of studies on the response of plants to rising CO₂ levels. The overwhelming theme is that plants, especially C3 plants, benefit from extra CO₂. There are two mechanisms by which CO₂ confers a growth benefit:

- Enhanced photosynthesis via the metabolic pathways described above.
- Increased water use efficiency. This arises because plants draw in CO₂ by opening the stomata (pores) on the leaf surface. When CO₂ is scarce the stomata must be kept wide open for long periods, allowing water to evaporate. Under enriched CO₂ conditions the stomata remain closed for longer periods, thus helping the plant retain water longer, and so increasing water use efficiency.

Specific effects of climate change on U.S. agriculture will be reviewed in Chapter 9.

2.1.3 Rising CO₂ and crop water use efficiency

Derying *et al.* (2016) surveyed evidence on crop water productivity (CWP), the yield per unit of water used, drawing attention to the potential for CO₂ both to enhance photosynthesis and to reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data (Free Air CO₂ Enrichment—see Chapter 9) on crop yield changes for maize (corn), wheat, rice, and soybean and combined

it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 emissions scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. They reported that models without CO₂ fertilization predicted CWP losses in every region, but those were more than offset by CO₂ fertilization so that all regions showed a net CWP gain. Deryng *et al.* (2016) also reported that negative impacts of warming on wheat and soybean yields were fully offset by CWP gains and mitigated by up to 90 percent for rice and 60 percent for maize.

Similarly, Cheng *et al.* (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO₂ uptake was accompanied by such large gains in CWP that global water use by plants had not increased, despite the extra biomass.

Deryng *et al.* (2016) assumed that climate change would “exacerbate water scarcity”. Yet while models do predict that drylands will expand under climate warming, current data show the opposite: greening is happening even in arid areas. Zhang *et al.* (2024) report that due to increased CO₂ levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”; at most only 4 percent of currently arid areas will see increased desertification.

2.1.4 CO₂ fertilization benefits in IPCC Reports

The IPCC has only minimally discussed global greening and CO₂ fertilization of agricultural crops. The topic is briefly acknowledged in a few places in the body of the IPCC 6th and earlier Assessment Reports but is omitted in all Summary documents. Section 2.3.4.3.3 of the AR6 Working Group I report, entitled “global greening and browning,” points out that the IPCC Special Report on Climate Change and Land had concluded with *high confidence* that greening had increased globally over the past 2-3 decades. It then discusses that there are variations in the greening trend among data sets, concluding that while they have *high confidence* greening has occurred, they have *low confidence* in the magnitude of the trend. There are also brief mentions of CO₂ fertilization effects and improvements in water use efficiency in a few other chapters in the AR6 Working Groups I and II Reports.

Overall, however, the Policymaker Summaries, Technical Summaries, and Synthesis Reports do not discuss the topic.

2.2 The Alkaline Oceans

2.2.1 Changing pH

A neutral aqueous solution has a pH of 7.0, while one with pH greater than 7.0 is alkaline (also termed basic) and with pH less than 7.0 is acidic. The modern-day global average pH of sea water is estimated to be 8.04 (Copernicus Marine Service 2025), down from an estimated value of 8.2 in pre-Industrial times (Gattuso and Hansson, 2011). As CO₂ concentrations in the atmosphere increased, the oceans absorbed more, which decreases their pH. Depending upon the oceans’ buffering capacity, they are expected to become somewhat less alkaline over time, consistent with the observed decrease in pH.

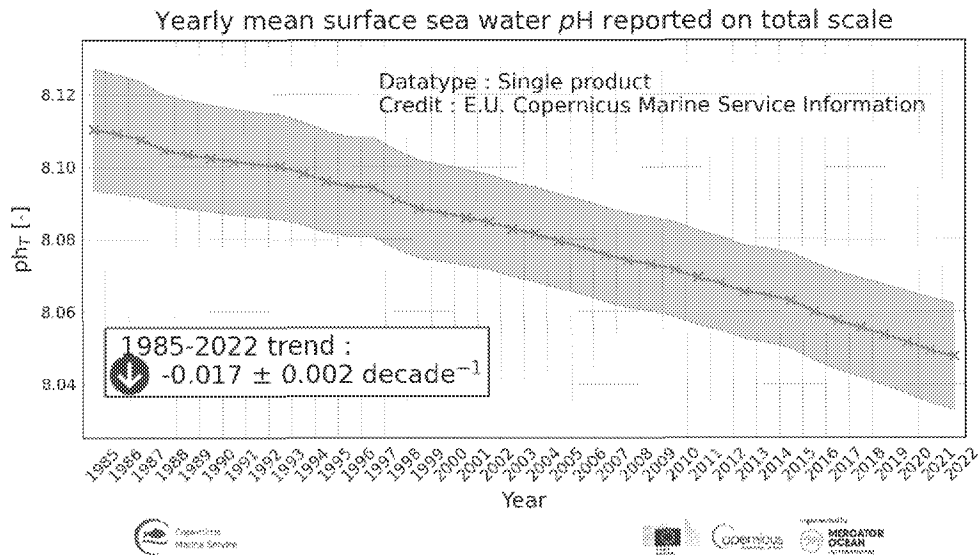


Figure 2.4: Ocean pH 1985 – 2022. Source: Copernicus Marine Service 2025

While this process is often called “ocean acidification”, it is a misnomer because the oceans are not expected to become acidic; “ocean neutralization” would be more accurate. Even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 to 7.0 (Kriessansen-Totton *et al.*, 2018). On the time scale of thousands of years, boron isotope proxy measurements show that ocean pH was around 7.4 or 7.5 during the last glaciation (up to about 20,000 years ago) increasing to present-day values as the world warmed during deglaciation (Rae *et al.*, 2018). Thus, ocean biota appear to be resilient to natural long-term changes in ocean pH since marine organisms were exposed to wide ranges in pH.

2.2.2 Coral reef changes

There are concerns that a decreasing pH of sea water will reduce the calcification rate of coral reefs. But coral reefs already endure large swings in pH, partly due to daily photosynthetic activity in the reef; measured pH values range from 9.4 during the day to 7.5 at night (Revelle and Fairbridge, 1957). De’ath *et al.* (2009) reported that a portion of Australia’s Great Barrier Reef (GBR, the world’s largest coral reef ecosystem) had experienced a 14 percent decline in calcification since 1990. This was tentatively attributed to increasing water temperature and decreasing pH. But Ridd *et al.* (2013) showed that report to have resulted from a biased data analysis that, when corrected, showed no change in calcification rates. Nevertheless, the alarm produced by the original paper has persisted as evidenced by the large number of published citations (541) to the original study compared to only 11 citations to the correction (as of 30 April 2025).

The most recent annual summary of GBR conditions from the Australian Institute of Marine Science indicates that coral production has rebounded strongly (AIMS, 2023). Figure 2.5 shows the results of the AIMS surveys of hard coral cover, expressed as a percentage of the reef area. Much of the decline in the GBR before 2011 turned out to be due to intense tropical cyclone activity (Beeden *et al.*, 2015) as well as a string of marine heatwaves, agricultural runoff and invasive species (Woods Hole, 2023). Given the reported declines in GBR calcification between 1990 and 2009 and the continued increase in atmospheric CO₂ levels the rebound has surprised some observers.

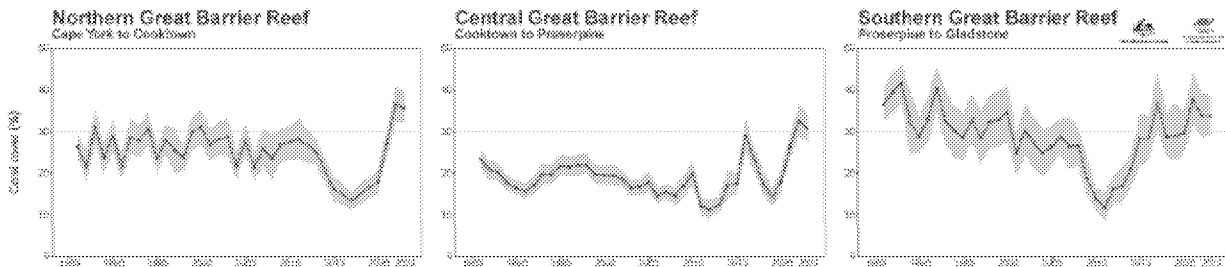


Figure 2.5 Hard coral cover of three regions of the Great Barrier Reef 1985 to 2023. Source: AIMS 2023.

It is being increasingly recognized that publication bias (alarming ocean acidification results preferred by high-impact research publications) exaggerates the reported impacts of declining ocean pH. An ICES Journal of Marine Science Special Issue addressed this problem with an article entitled, *Towards a Broader Perspective on Ocean Acidification Research*. In the Introduction to that Special Issue, H. I. Browman stated, “As is true across all of science, studies that report no effect of ocean acidification are typically more difficult to publish.” (Browman, 2016).

Similarly, a meta-analysis (Clements *et al.*, 2021) of the negative effects of ocean acidification on reef fish behavior found what they called a “decline effect”: initially dramatic conclusions published in prominent journals showing apparently large impacts of acidification tended to be followed up by subsequent studies on larger sample sizes yielding much smaller and typically non-existent effects. They call for their colleagues to improve research practices to counter the “decline effect”:

[The] vast majority of studies with large effect sizes in this field tend to be characterized by low sample sizes, yet are published in high-impact journals and have a disproportionate influence on the field in terms of citations. We contend that ocean acidification has a negligible direct impact on fish behavior, and we advocate for improved approaches to minimize the potential for a decline effect in future avenues of research (Clements *et al.*, 2021).

In summary, ocean life is complex and much of it evolved when the oceans were acidic relative to the present. The ancestors of modern coral first appeared about 245 million ago; as can be seen from Figure 2.2, CO₂ levels for more than 200 million years afterward were many times higher than they are today. Much of the public discussion of the effects of ocean “acidification” on marine biota has been one-sided and exaggerated. There is a known tendency for studies reporting dramatic effects on things like coral cover and fish behavior to get published in high-impact journals and receive widespread press coverage, then subsequent research rebutting those findings receives little attention.

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3 HUMAN INFLUENCES ON THE CLIMATE

Chapter Summary:

The global climate is naturally variable on all time scales. Anthropogenic CO₂ emissions add to that variability by changing the total radiative energy balance in the atmosphere.

The IPCC has downplayed the role of the sun in climate change but there are plausible solar irradiance reconstructions that imply it contributed to recent warming.

Climate projections are based on IPCC emission scenarios that have tended to exceed observed trends. Most academic climate impact studies in recent years are based upon the extreme RCP 8.5 scenario that is now considered implausible; its use as a business-as-usual scenario has been misleading.

Carbon cycle models connect annual emissions to growth in the atmospheric CO₂ stock. While models disagree over the rate of land and ocean CO₂ uptake, all agree that it has been increasing since 1959.

3.1 Components of radiative forcing and their history

3.1.1 Historical radiative forcing

A changing climate has been the norm throughout the Earth's 4.6-billion-year history. The Earth's temperature and weather patterns change naturally over timescales ranging from decades to millions of years. Natural variations in the surface climate originate in two ways. Internal climate fluctuations associated with circulations in the atmosphere and ocean exchange energy, water, and carbon between the atmosphere, oceans, land, and ice. External influences on the climate system include variations in the energy received from the sun and the effects of volcanic eruptions. Human activities influence climate through changing land use and land cover. Humans are also changing the composition of the atmosphere by emissions of CO₂ and other greenhouse gases and by altering the concentration of aerosol particles in the atmosphere.

The earth is warmed by the sunlight it absorbs and is cooled by the heat it radiates to space. Averaged over the Earth's surface, each of these processes involve power flows of about 240 Watts per square meter (W/m²). When they are in balance, there are no net external causes of warming or cooling. Both human and natural influences on the climate alter this balance and so cause the climate to change.

Influences on the Earth's energy balance at the top of the atmosphere are quantified by "radiative forcing", the extent to which they disturb the warming/cooling balance; a positive forcing warms while a negative forcing cools. The IPCC's estimated history of major components of radiative forcing since 1750 is shown in the following two figures from its AR6.

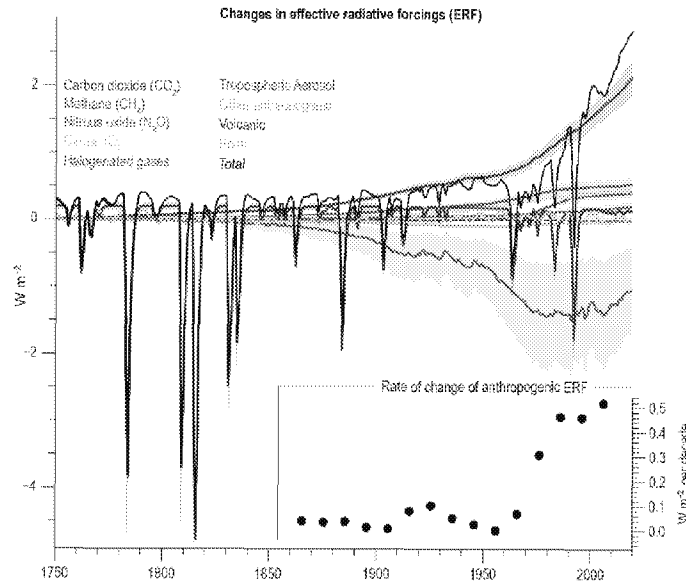


Figure 3.1.1: IPCC estimates of radiative forcing components over time. Shading indicates uncertainty ranges. Source: AR6 WGI Ch2 Fig. 10

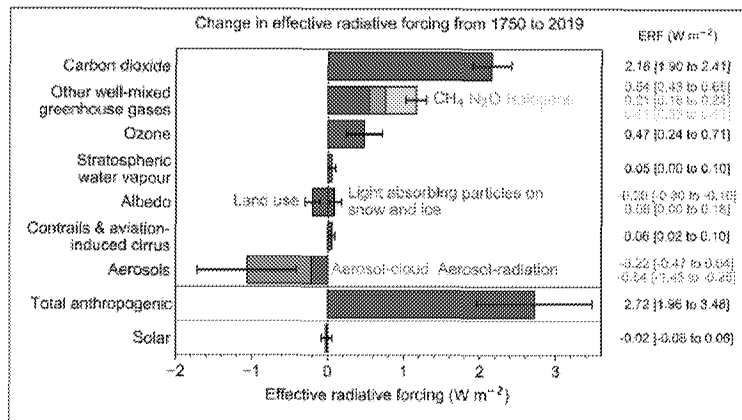


Figure 3.1.2 IPCC estimates of radiative forcing component changes from 1750 to 2019. Source: AR6 WGI Ch 7 Fig. 7-6.

These graphs show that the total radiative forcing is comprised of both natural and anthropogenic components. Carbon dioxide is the largest human influence on the climate and the one most relevant to the influence of fossil fuel use. It exerts a warming influence by decreasing the cooling power of the atmosphere. Emissions of CO_2 are accumulating in the atmosphere, as described in the following section, so that the warming influence is growing. Other greenhouse gases (methane, nitrous oxide, halogens, and ozone) act similarly, currently adding another 75 percent to CO_2 's warming. Aerosols exert an overall cooling effect, although with large uncertainties in the way they catalyze the formation of reflective clouds. As a result, understanding the causes of recent warming requires not just identifying the warming effects of CO_2 , but also the more uncertain cooling effects of aerosols.

The IPCC assesses the change in the radiative forcing by the sun to be negligible, based on their preference for data reconstructions that imply minimal solar change since preindustrial times. But Connolly *et al.* (2021) reviewed sixteen different Total Solar Irradiance (TSI) reconstructions in the literature

covering the years 1600-2000; the reconstructions vary from almost no change in TSI to a relatively large upward trend. Those authors note that the variation in TSI reconstructions combined with variations in surface temperature reconstructions allows for inferences consistent with either no or most 20th century warming being attributable to the sun.

A particularly thorny issue is the gap in TSI data between 1989 and 1991 due to a delay in the launch of a monitor following the Space Shuttle Challenger disaster on January 28 1986. This delay prevented a replacement satellite from being launched in time to overlap with, and its readings to be intercalibrated with, the prior system (Zacharias 2014, Scafetta *et al.* 2019). This is called the ACRIM (Active Cavity Radiometer Irradiance Monitor) gap problem. The question of whether there is an upward trend in TSI over 1978 to 2018 hangs on how the ACRIM data gap is filled. Connolly *et al.* (2021) found that the IPCC's consensus statements on solar forcing were formulated prematurely through the suppression of dissenting scientific opinions.

Another natural radiative forcing component is volcanic aerosols, which exert an episodic cooling influence. Box 4.1 in the IPCC AR6 Report addresses the climate impact of volcanic eruptions, noting three explosive volcanic eruptions that occurred in the first half of the 19th century. This included the 1815 Tambora eruption that resulted in the 'year without summer', with multiple harvest failures across the Northern Hemisphere. There is uncertainty about the sign of the relatively small forcing due to the submarine volcano Hunga Tonga which erupted in 2022 (Jenkins *et al.* 2023, Schoeberl *et al.* 2024).

Figure 3.1.1 shows that the anthropogenic forcing component was negligible before about 1900 and has increased steadily since, rising to almost 3 W/m² today. However, this is still only about 1 percent of the unperturbed radiation flows, making it a challenge to isolate the effects of anthropogenic forcing; state-of-the-art satellite estimates of global radiative energy flows are only accurate to a few W/m².

Natural sources of global energy imbalance other than volcanoes and total solar irradiance (TSI) are not included in these graphs because they remain largely unknown.

3.1.2 Change in atmospheric CO₂ since 1958

Carbon dioxide's warming influence depends on how much "extra" CO₂ accumulates in the atmosphere- *i.e.*, its concentration above the preindustrial value of 280 ppm. The CO₂ level as recorded at the Mauna Loa observatory in Hawaii, generally used as the representative global average concentration, is available online at [[HYPERLINK "https://gml.noaa.gov/ccgg/trends/index.html"](https://gml.noaa.gov/ccgg/trends/index.html)]. The concentration was about 316 ppm at the start of the record in 1959 and is now about 430 ppm, a 36 percent increase. At the end of the last glaciation CO₂ levels had fallen to about 180 ppm. As discussed in Chapter 2, C3 plants begin dying at CO₂ levels below about 140 ppm and C4 plants at levels below 100 ppm, so if CO₂ levels had continued falling plant life would have been imperiled.

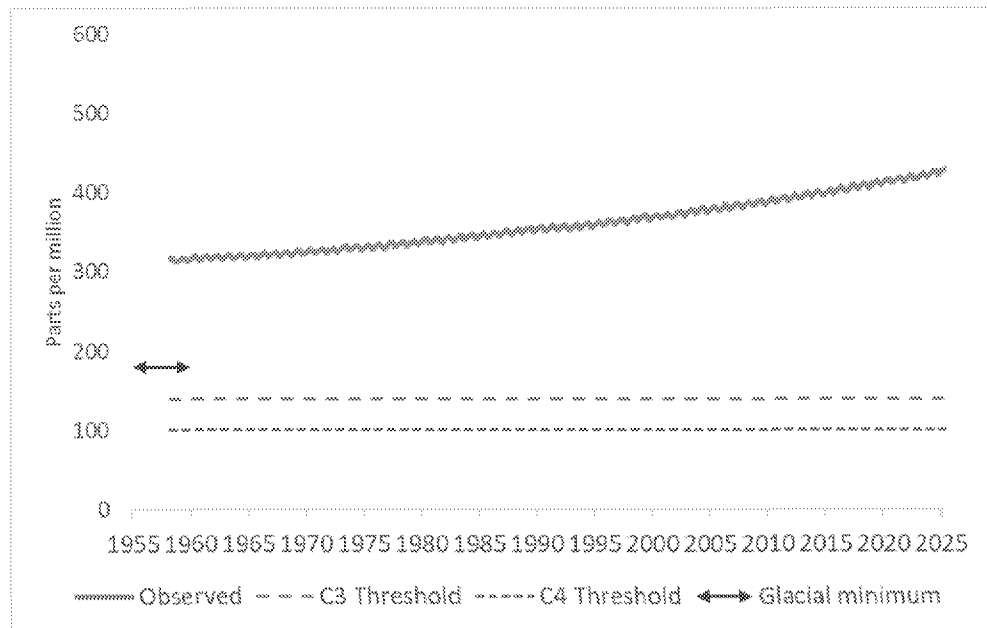


Fig. 3.1.3. Yearly average atmospheric CO₂ concentrations (1959-2025) in ppm measured at Mauna Loa (blue). C3 Threshold: Level below which C3 plants begin dying (140 ppm, see Chapter 2). C4 Threshold: Level below which C4 plants begin dying (100 ppm, see Chapter 2). Glacial minimum: Minimum level during recent glaciations (purple arrow). CO₂ data source: [HYPERLINK "<https://gml.noaa.gov/ccgg/trends/index.html>"]

The annual increase in concentration is only about half of the CO₂ emitted because land and ocean processes currently absorb “excess” CO₂ at a rate approximately 50 percent of the human emissions. Future concentrations, and hence future human influences on the climate, therefore depend upon two components: (1) future rates of global human CO₂ emissions, and (2) how fast the land and ocean remove extra CO₂ from the atmosphere. We discuss each of these in turn.

3.2 Future emission scenarios and the carbon cycle

3.2.1 Emission scenarios

Assessing the dangers of future GHG emissions requires assumptions about what those emissions will be. Future emissions, and hence human influences on the climate, will depend upon future demographics, economic activity, regulation, and energy and agricultural technologies. Various assumptions about each of those lead to projections of greenhouse gas emissions and concentrations, aerosol concentrations, and changes in land use, which ultimately can be combined into assumptions about anthropogenic radiative forcing.

The great uncertainties about these many factors make it impossible to precisely predict future emissions. Instead, the IPCC has created various sets of scenarios meant to span a plausible range of possibilities for population, economy, and technologies. Recent versions of the scenarios are labeled by a number indicating the anthropogenic radiative forcing expected in 2100 under that scenario. Thus, a scenario labeled with a “6” corresponds to 6 W/m² of human-induced radiative forcing (warming) at the end of the century. (Recall current anthropogenic radiative forcing is about 2.7 W/m².)

Although the IPCC does not claim its emission scenarios are forecasts, they are often treated as such. Comparisons of past scenario groups against observations show that IPCC emission projections tend to overstate actual subsequent emissions. For the IPCC Third and Fourth Assessment Reports a set of emission projections from the *Special Report on Emission Scenarios* was used; these were referred to as the SRES scenarios. McKittrick *et al.* (2012) showed that, when converted to per capita values, the SRES scenario emissions distribution was skewed upwards and incompatible with observed trends. McKittrick and Wood (2013) further showed that global energy market dynamics constrained global per capita CO₂ emissions to an extent not reflected in IPCC scenarios. The bias of the SRES scenarios was confirmed by the later analysis of Hausfather *et al.* (2019) who showed that observed atmospheric CO₂ concentrations tracked the low end of the SRES range and also of subsequent IPCC scenario ranges (Figure 3.2.1).

For AR5 the IPCC developed a new set of scenarios called the Representative Concentration Pathways (RCPs). These were identified by a number representing the increase in forcing and were thus called RCP2.6, RCP4.5, RCP6.0 and RCP8.5. RCP2.6 (implying an anthropogenic radiative forcing in 2100 of 2.6 W/m²) describes a GHG concentration pathway leading to warming well below 2°C. At the other end of the scale RCP8.5 is an extreme outcome implying nearly 5°C warming from 1900 to 2100.

RCP8.5 came to be referred to as the no-policy baseline, or “business-as-usual” scenario in both the academic literature and popular media. It was therefore used to generate the reference outcome supposedly representing the 21st century world in the absence of increasingly stringent emission reduction policies. But RCP8.5 was intended as a low-probability high emissions scenario and its use as a business-as-usual baseline has been criticized as grossly misleading.¹ Hausfather and Peters (2020) writing in a commentary in *Nature*, pointed out that RCP8.5 was developed as an extreme worst-case, and its misuse as a “business as usual” baseline has resulted in a large number of misleading studies and media reporting.

The implausibility of the RCP8.5 scenario was examined by Burgess *et al.* (2021). They noted that RCP8.5 has already diverged from observed trends in energy use and the near future trends diverge sharply from those of the International Energy Agency (IEA), which provides market-based projections of energy use for the coming decades. The IEA trends, which are based on plausible extrapolations of current economic and demographic trends, run below the entire envelope of RCP projections, implying not only that RCP8.5 is dubious, but that even lower emission scenarios are unlikely.

Widespread use of RCP8.5 has created a bias towards alarm in the climate impacts literature. The extent of this problem was confirmed in a literature analysis by Pielke Jr. and Ritchie (2020). They found that some 16,800 scientific papers published between 2010 and 2020 used the RCP8.5 scenario, with about 4,500 of the articles linking RCP8.5 to the concept of “business-as-usual”. Their analysis showed how RCP8.5 was misused not only by individual researchers, but also by influential science agencies like the IPCC and the U.S. National Climate Assessment (USNCA), which has directly led to misleading coverage in prominent media outlets.

¹ This extreme scenario is useful for modelers, since a large forcing generates a large response (warming) making it easier to assess a model’s sensitivity. But that’s very different than claiming it is a plausible future outcome.

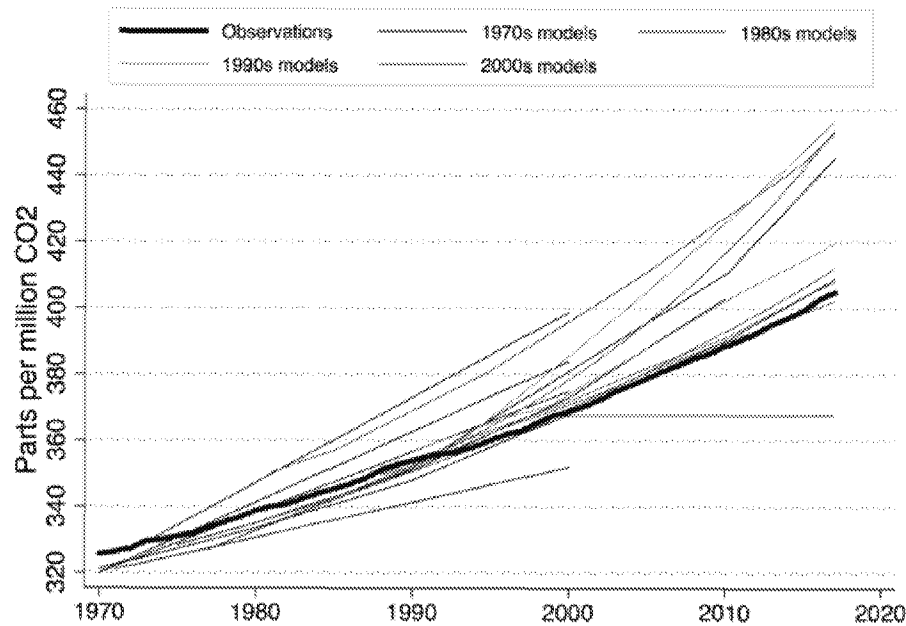


Figure 3.2.1 Comparison of observed atmospheric CO₂ levels (black line) with scenario projections (colored lines, mainly IPCC) since the 1970s. Source: Hausfather *et al.* (2019) Figure S4.

Pielke and Ritchie (2020) reported new studies using RCP8.5 were published at a rate of about 20 per day, with about two per day specifically linking RCP8.5 and “business as usual.” They conclude that the climate research community has spent a decade “committing scientific resources to science fiction” and that “The scientific literature has become imbalanced in an apocalyptic direction.”

The IPCC developed a new set of scenarios for AR6, the “Shared Socioeconomic Pathway” (SSP) scenarios, which have continued the bias shown in the RCP and SRES scenarios. Figure 3.2.2 shows total global observed CO₂ emissions compiled by the International Energy Agency (IEA) merged with the emission projection from the IEA taking account of energy use projections and current policies. The other lines show the range of IPCC SSP scenarios (SSP1-SSP5). As of 2023, global CO₂ emissions have been tracking well below SSP7.0 and are even below SSP2-4.5.

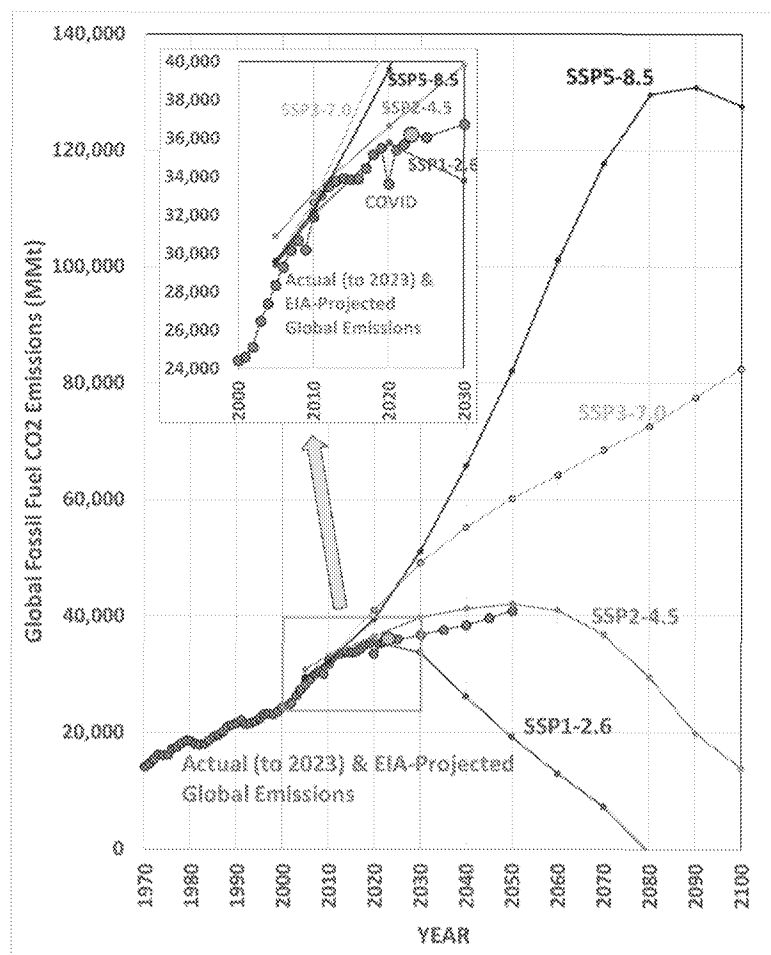


Figure 3.2.2. Observed and projected CO₂ emissions. Source: IPCC (SSP scenarios) and Energy Information Administration (EIA). Green: observed historical emissions and EIA projections. Other lines: SSP1-5. Data source: Friedlingstein *et al.* (2024).

3.2.2 The carbon cycle relating emissions and concentrations

Carbon dioxide emissions from fossil fuel burning (and to a lesser extent deforestation and cement production) have led to steadily increasing CO₂ concentrations in the atmosphere, as shown in Fig. 3.1.3. The relation between emissions and concentration is determined by the global carbon cycle of land and ocean processes that exchange carbon with the atmosphere. Our understanding of these processes was reviewed by Crisp *et al.* (2021).

There are about 850 Gt of carbon (GtC) in the Earth's atmosphere², almost all of it in the form of CO₂. Each year, biological processes (plant growth and decay) and physical processes (ocean absorption and outgassing) exchange about 200 GtC of that carbon with the Earth's surface (roughly 80 GtC with the land and 120 GtC with the oceans). Before human activities became significant, removals from the atmosphere were roughly in balance with additions. But burning fossil fuels (coal, oil, and gas) removes carbon from the ground and adds it to the annual exchange with the atmosphere. That addition (together with a much

² Because CO₂ is chemically transformed through the course of the carbon cycle, it is more convenient to track atoms of carbon rather than molecules of CO₂. One gigatonne of carbon (GtC) is equivalent to about 3.7 Gt of CO₂.

smaller contribution from cement manufacturing) amounted to 10.3 GtC in 2023, or only about 5 percent of the annual exchange with the atmosphere.

The carbon cycle accommodates about 50 percent of humanity’s small annual injection of carbon into the air by naturally sequestering it through plant growth and oceanic uptake, while the remainder accumulates in the atmosphere (Ciais *et al.*, 2013). For that reason, the annual increase in atmospheric CO₂ concentration averages only about half of that naively expected from human emissions.

To project future CO₂ concentrations in the atmosphere, and hence future human influences on the climate, it is important to know how the carbon cycle might change in the future. The historical near constancy of that 50 percent fraction means that the more CO₂ humanity has produced, the faster nature removed it from the atmosphere. That 50 percent fraction changes somewhat from year to year due to natural carbon cycle imbalances from El Nino, La Nina, and varying weather patterns. There was also a substantial additional reduction in atmospheric CO₂ after the 1991 eruption of Mt. Pinatubo, a curious result that has yet to be explained (Angert *et al.*, 2004).

The main processes that remove excess CO₂ from the atmosphere are increased growth of land vegetation (especially at high latitudes), some increase in the sequestering of carbon in soils, and uptake of CO₂ by the ocean due to the increasing partial pressure of atmospheric CO₂ over that of CO₂ dissolved in the ocean. All twenty land carbon cycle models tracked by the Global Carbon Project (Friedlingstein *et al.*, 2024) show land processes have been removing excess CO₂ at an increasing rate since 1959. This is consistent with a “global greening” phenomenon (Chapter 2.1) observed by satellites since monitoring of global greenness began in 1982.

While land vegetation has been responding positively to more atmospheric CO₂, uptake of extra CO₂ by ocean biological processes remains too uncertain to be measured reliably. Our current understanding of these and many more carbon cycle processes was reviewed by Crisp *et al.* (2021).

CO₂ uptake by land processes

The uptake of extra CO₂ from the atmosphere by land surface processes (as also inferred from global greening) has been modeled with 20 different dynamic global vegetation models, the outputs of which are updated every year by the Global Carbon Project (Friedlingstein, 2024). As seen in Fig. 3.2.3, all of those models agree that vegetation and soils have been sequestering carbon from the atmosphere. But we also see that the long-term trends over 1959 to 2023 (65 years) vary widely between models, by nearly a factor of 7. This demonstrates that there remains considerable uncertainty in how fast land processes are removing CO₂ from the atmosphere, which in turn creates uncertainty in future atmospheric CO₂ concentrations, which then produce uncertainty in climate model simulations of future climate change.

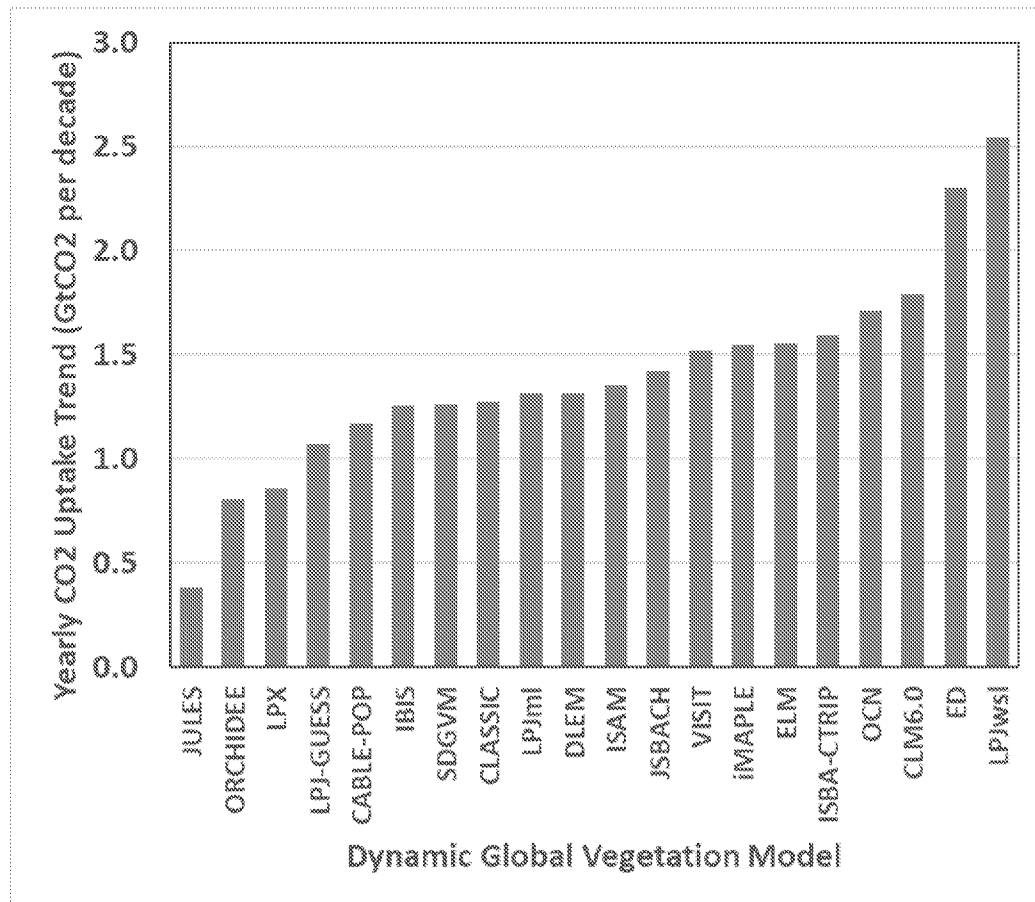


Figure 3.2.3 Trends of annual CO₂ uptake (GtCO₂ per year per decade) by land processes during 1959-2023 simulated by 20 different dynamic global vegetation models periodically reported by the Global Carbon Project (Friedlingstein, 2024).

CO₂ uptake by ocean processes

The uptake of extra CO₂ from the atmosphere by ocean processes has been modeled with 10 different ocean biogeochemistry models, the outputs of which are updated every year by the Global Carbon Project (Friedlingstein, 2024). Like the results from the land models, all of the ocean models agree that the global oceans have been sequestering carbon from the atmosphere at an increasing rate during 1959-2023 (Fig. 3.2.4). Unlike the land models, however, the ocean models show much better agreement with each other, with the model producing the fastest increasing CO₂ uptake being only 65 percent faster than the model with the most slowly increasing CO₂ uptake. In spite of the relative agreement among models, Friedlingstein *et al.* (2022) notes that there is substantial discrepancy between the different methods on the strength of the ocean sink over the last decade, particularly in the Southern Ocean.

Note that the average trend in CO₂ uptake across all land models in Fig. 3.2.3 is 25 percent larger than the average trend in ocean uptake. This suggests land processes are increasing in their ability to remove CO₂ faster than ocean processes are increasing their CO₂ sequestration.

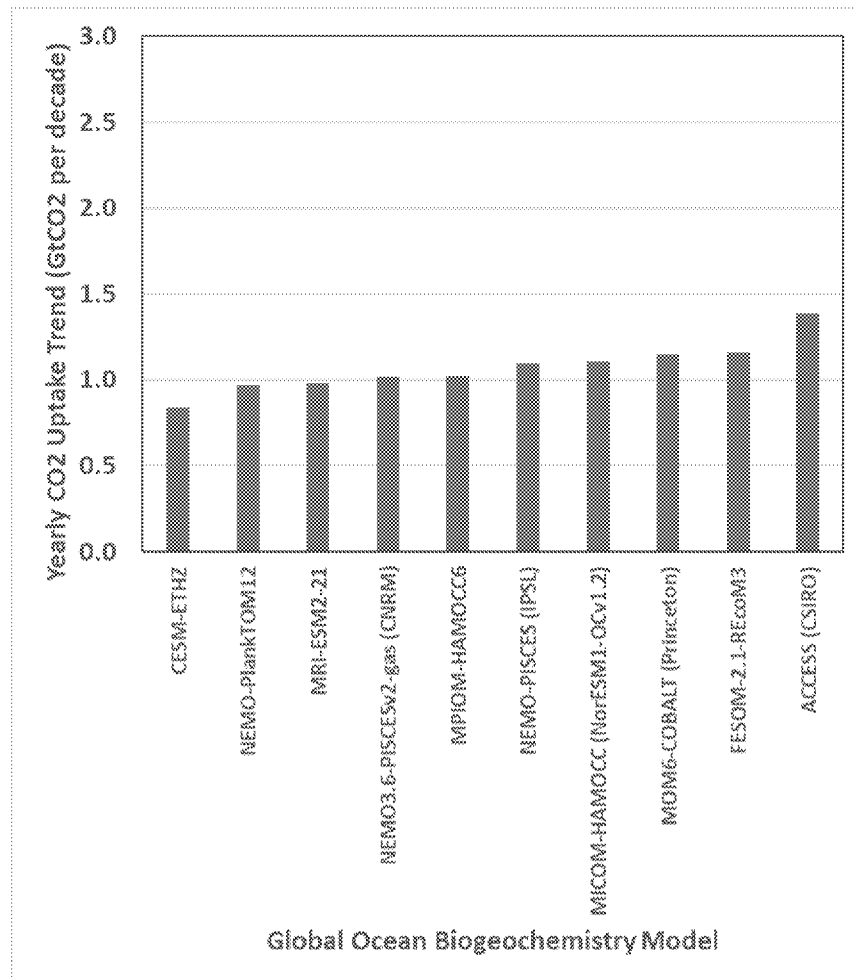


Figure 3.2.4 Trends of annual CO₂ uptake (GtCO₂ per year per decade) by ocean processes during 1959-2023 simulated by 10 different ocean biogeochemistry models periodically reported by the Global Carbon Project (Friedlingstein, 2024).

3.3 Urbanization influence on temperature trends

Historical temperature data over land has been collected mainly where people live. This raises the problem of how to filter out non-climatic warming signals due to Urban Heat Islands (UHI) and other changes to the land surface. If these are not removed the data might over-attribute observed warming to greenhouse gases. The IPCC acknowledges that raw temperature data are contaminated with UHI effects but claims to have data cleaning procedures that remove them. It is an open question whether those procedures are sufficient.

AR6 downplayed this issue by saying (WGI p. 235) that no recent evidence had emerged to alter the AR5 finding that urbanization causes an upward bias of no more than 10 percent in the global land surface warming trend. AR5 (WGI p. 189) also cited the 10 percent upper bound without citing a source. AR4 (WGI p. 244) cited Jones *et al.* (1990) and Peterson *et al.* (1999) as the basis of the claim. Peterson *et al.* had failed to find any difference in trends between rural and urban samples, although their definition of rural included local populations up to 10,000 persons while the relative influence of urbanization begins well below that (Spencer *et al.*, 2025). Jones *et al.* compared rural/urban warming in three regions: Eastern Australia, Eastern China and Western Soviet Union. Their definition of “rural” included towns of up to

10,000 in the former Soviet Union and up to 100,000 in China. They found relative warming biases greater than 10 percent in these areas but conjectured that the urbanization effect averaged over the areas they did not examine would bring the global land bias to under 10 percent of the observed warming trend.

Several papers appeared in print prior to the IPCC AR4 that argued that the warming effect of UHIs added a relatively large (30-50%) component to observed warming and was not simulated by climate models (de Laat and Maurellis 2006, McKittrick and Michaels 2007). These findings were based on correlations between locations of maximum warming over land with locations of maximum socioeconomic development. AR4 asserted (p. 244) that these correlations were an artefact of natural atmospheric circulations and were in fact statistically insignificant, and on that basis set the findings aside. Their claim was controversial because it was presented with no supporting evidence. McKittrick (2010) and McKittrick and Nierenberg (2010) showed that taking into account various conjectured alternative explanations for the correlations did not affect their significance. AR5 (p. 189) conceded that AR4 had provided “no explicit evidence” for its assessment and further acknowledged, based on these papers, that there was “significant evidence for such contamination of the record” i.e. a warming bias in the land record. However as already noted, elsewhere in the AR5 report they carried forward AR4 claim that it was less than 10 percent of observed warming. Further they provided no caution about using the land record for climate measurement despite conceding the evidence for UHI contamination. Recently Soon *et al.* (2023) estimated an urbanization bias in the Northern Hemisphere land record over 1850-2018 sufficient to increase the trend in the blended record from 0.55°C to 0.89°C per century.

Some studies providing evidence against UHI contamination compared warming rates between rural and urban locations (Jones *et al.* 1990, Peterson *et al.* 1999, Wickham *et al.* 2013). It is not known whether such methods would be capable of detecting UHI bias even when present. The influence of UHI warming is logarithmic in population, in other words it is strongest at low population density then levels off as local urbanization expands (Oke 1973, Spencer *et al.* 2025). Hence failure to find a difference in warming rates between urban and rural stations does not prove the absence of UHI contamination. McKittrick (2013) provided an empirical demonstration in which the rural/urban trends were not significantly different in a data set shown on other grounds to be contaminated with UHI bias.

Parker (2006) examined a sample of urban locations and found no difference in trends between subsets partitioned according to nighttime wind speed, concluding on this basis that urbanization could not be a significant factor. Here again the question is whether such a method would find UHI bias even if present. McKittrick (2013) presented an example in which UHI-contaminated data did not exhibit significant trend differences when stratified according to wind speed.

The challenge in measuring UHI bias is relating local temperature change to a corresponding change in population or urbanization, rather than to a static classification variable such as rural or urban. Spencer *et al.* (2025) used newly available historical population archives to undertake such an analysis and found evidence of significant UHI bias in U.S. summertime temperature data.

In summary, while there is clearly warming in the land record, there is also evidence that it is biased upward by patterns of urbanization and that these biases have not been completely removed by the data processing algorithms used to produce climate data sets.

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PART II: CLIMATE RESPONSE TO CO₂ EMISSIONS

4 CLIMATE SENSITIVITY TO CO₂ FORCING

Chapter Summary

There is growing recognition that climate models are not fit for the purpose of determining the Equilibrium Climate Sensitivity (ECS) of the climate to increasing CO₂. The IPCC has turned to data-driven approaches including historical data and paleoclimate reconstructions, but their reliability is diminished by data inadequacies.

Data-driven ECS estimates tend to be lower than climate model-generated values. The IPCC AR6 upper bound for the likely range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by paleoclimatic data. The IPCC AR6 lower bound for the likely range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound is less justified; evidence since the AR6 finds the lower bound of the *likely* range to be around 1.8°C.

4.1 Introduction

The climate's response to increasing concentrations of CO₂ is central to the scientific debate on anthropogenic climate change, and so also to the public debate on “climate action.” The simplest measure of that response is the rise in the global average surface temperature, quantified by the Equilibrium Climate Sensitivity (ECS). ECS is defined as the amount of warming expected in response to a doubling of CO₂ from its pre-industrial concentration of 280 ppm, after all climate components have had time to adjust. Some components, like temperatures in the lower atmosphere (troposphere), adjust rapidly, while others such as the deep ocean and cryosphere might take as long as centuries. A related measure, the Transient Climate Response (TCR), better describes the shorter time scales; it is defined as the amount of warming when the CO₂ concentration is doubled by rising one percent annually for 70 years.

The 1979 Charney Report for the U.S. National Academy of Sciences (National Research Council 1979) proposed that the most likely ECS was $3.0 \pm 1.5^\circ\text{C}$. The IPCC repeatedly reaffirmed that range with only minor variations until its most recent AR6. AR5 termed 1.5–4.5°C as the *likely* range (66 percent probability) and stated that ECS is *extremely unlikely* (95 percent probability) to be below 1.0°C and *very unlikely* (90 percent probability) to exceed 6.5°C.

The uncertainty in ECS has remained stubbornly wide, despite many individual studies that claimed to narrow it (Hausfather 2023). Most recently, AR6 narrowed the *likely* range to 2.5–4.0°C and deemed the *very likely* range to be 2.0–5.0°C. This narrowing on the low end is disputed, as will be discussed below.

Uncertainties in ECS are highly consequential for policy making. As will be discussed in Chapter 11, economic models use ECS values to project the costs of CO₂ emissions. The traditional value (3.0 °C) has typically yielded modest global social costs of CO₂ emissions, sufficient to justify some policy actions, but mostly deferred to later in this century. If ECS is very high (above 4.5°C) immediate aggressive emission controls become more imperative, whereas no CO₂ emission controls are economically justifiable for ECS below 2.0°C (Dayaratna *et al.* 2016, 2020). Obtaining a precise estimate is impossible, so policy making needs to account for the uncertainty.

By itself, the equilibrium warming effect of a doubling of atmospheric CO₂ is slightly more than 1°C (Soden and Held 2006). Larger values of ECS arise from positive feedbacks that amplify the CO₂ warming. Water vapor feedback is positive: a warmer atmosphere might have more water vapor, which itself is a powerful greenhouse gas. Warmer temperatures also result in less snow and sea ice cover, allowing the

Earth to absorb more of the sun's radiation. Some simple estimates of these feedbacks increase the ECS to around 2°C (Sherwood *et al.*, 2020). Larger values of ECS are associated with positive cloud feedbacks.

Climate scientists use multiple lines of evidence to determine the Equilibrium Climate Sensitivity:

- Climate model simulations
- Historical observations
- Paleoclimatic reconstructions
- Process understanding of feedbacks

4.2 Model-based estimates of climate sensitivity

The ECS ranges given in IPCC AR4 and AR5 were obtained primarily by examining the behavior of large-scale climate models, also called General Circulation Models (GCMs). However, the IPCC changed course in its AR6 when it turned to a more direct data-driven methodology. Here we discuss some of the pitfalls of using GCMs to try to determine the Earth's climate sensitivity.

In principle, ECS is an emergent property of GCMs—that is, it is not directly parameterized or tuned, but rather emerges in the results of the simulation. Otherwise plausible GCMs and parameter selections have been discarded because of perceived conflict with an expected warming rate, or aversion to a model's climate sensitivity being outside an accepted range (Mauritsen *et al.* 2012). This practice was commonplace for the models used in AR4; modelers have moved away from this practice with time. However, even in a CMIP6 model, Mauritsen and Roeckner (2020) state the following regarding their Max Planck Institute (MPI) climate model (emphasis added):

“We have documented how we tuned the MPI-ESM1.2 global climate model to match the instrumental record of warming; an endeavor which has clearly been successful. Due to the historical order of events, the choice was to do this practically by **targeting an ECS of about 3 K using cloud feedbacks**, as opposed to tuning the aerosol forcing.”

In other words, the MPI modelers chose an ECS value of 3°C and then tuned the cloud parameterizations to match their intended result.

As noted, direct warming from CO₂ doubling is only about 1°C (Soden and Held 2006); further warming arises from climate feedbacks that are not explicitly resolved by the GCM but rely on parameterizations of physical processes. Higher values of ECS arise primarily from assumed positive cloud feedbacks, whereas the magnitude and even the sign of the feedbacks are very uncertain. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle (Curry and Webster, 1999). It is difficult for GCMs to simulate any of these processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks.

ECS can be determined from climate model simulations by doubling the concentration of CO₂ and allowing several centuries for the warming to equilibrate. To avoid the need for such long simulations, “effective climate sensitivity” is commonly evaluated from a 150-year simulation in response to a sudden quadrupling of CO₂.

The spread of ECS values from the CMIP5 ensemble of climate models used in AR5 was 2.0–4.7°C; that range increased for the CMIP6 models used in AR6 to between 1.8 and 5.7°C (Chen *et al.*, 2021, Scafetta 2021, see Figure 4.1). Far from resolving the model-based climate sensitivity the range appears to be growing. The main cause of the overall upward shift in ECS in CMIP6 relative to CMIP5 is a larger positive cloud feedback, driven by changes to the cloud parameterizations in many CMIP6 models (Zelinka *et al.*, 2020)

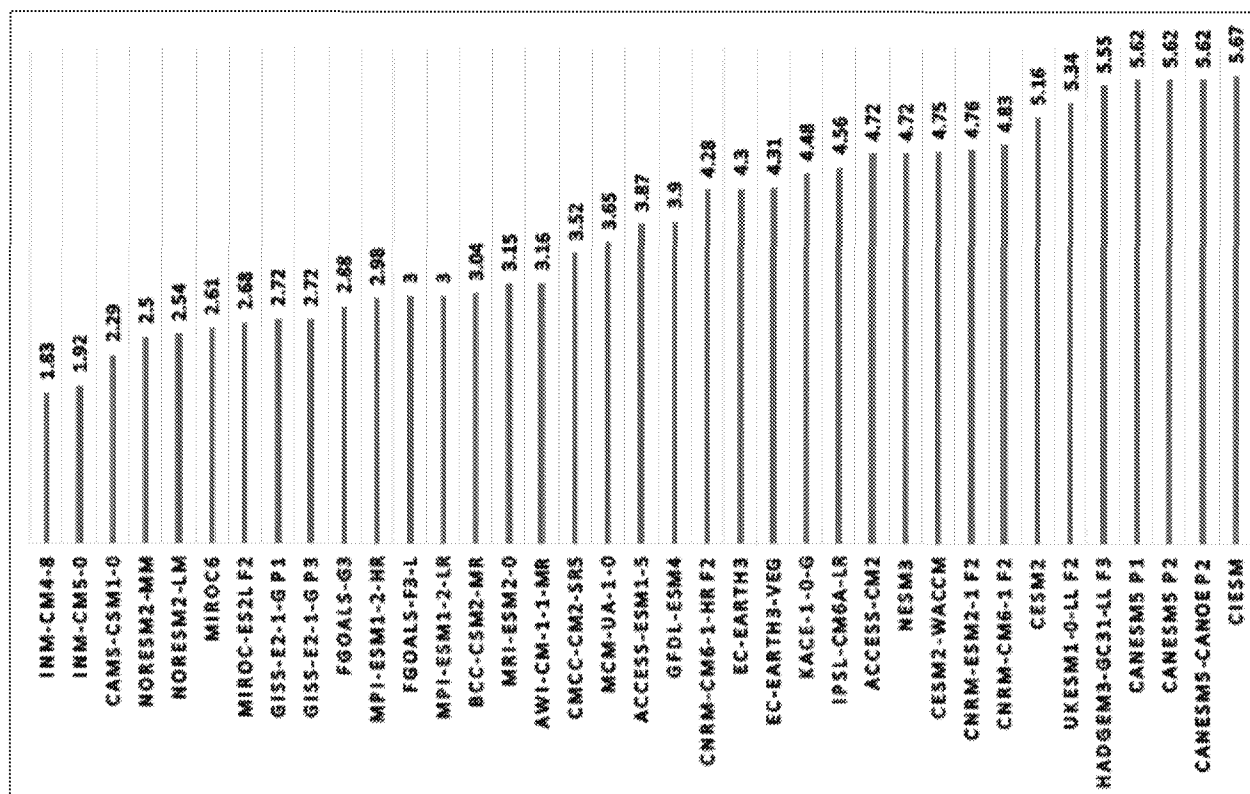


Figure 4.1 Equilibrium Climate Sensitivities in °C of 37 climate models from the CMIP6 ensemble. Identifiers for the various models appear along the horizontal axis. From (Scafetta, 2021)

Because of concerns about model tuning and the high sensitivity to cloud parameterizations, the IPCC AR6(2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying instead on data-driven methods.

4.3 Data-driven estimates of climate sensitivity

Climate sensitivity can also be estimated from instrumental records of surface temperatures and ocean heat content, combined with estimates of how climate forcings (e.g., greenhouse gases, solar, volcanoes, aerosols) have changed in the past (Otto *et al.*, 2013). Using this information, a simple empirical model called an Energy Balance Model can be employed. It requires estimating a feedback parameter whose uncertainties are highly amplified in the resulting ECS (Roe and Baker, 2007).

The accuracy of the data-driven methods depends on the quality of the input data. Assumptions are needed about ocean heat storage, and good data is only available for recent decades. The greatest source of uncertainty is the amount and composition of aerosol particles and their interactions with cloud radiative properties (the so-called aerosol indirect effect; see Figures 3.1.1, 3.1.2). Climate models exhibit warming in response to GHGs but cooling in response to aerosols (Schwartz *et al.*, 2007). Observed 20th century warming can be shown to be consistent either with low ECS and low aerosol cooling, or high ECS and high aerosol cooling. Since fossil fuel use adds both GHGs and aerosols to the atmosphere, both effects need to be estimated to isolate the warming effect of CO₂.

Paleoclimate proxies are also used to evaluate the sensitivity of past climates by comparing paleoclimate changes in the Earth's temperatures to estimates of changes in forcings. The two most informative periods are the last glacial maximum (around 20,000 years ago), which was about 3–7°C colder than today, and a mid-Pliocene period (roughly three million years ago), which was 1–3°C warmer than today. The limits on cooling during the last glacial maximum give the best single evidence that high values of climate sensitivity are unlikely. However, paleoclimate estimates are associated with very large uncertainties in the estimated temperatures and forcings. Further, estimates of climate sensitivity based on past climate states might not be applicable to the current state of the climate system.

A recurring theme in the climate literature is that ECS estimates based on historical data are smaller than ECS estimates inferred from climate models (Sherwood and Forest 2024). About 15 estimates based on historical data appeared in the peer-reviewed literature between 2012 and 2024 yielding ECS best estimates between 1.0°C and 2.5°C, although critics have questioned some of the methods and the data quality. For AR6, the IPCC placed primary weight on the results of Sherwood *et al.* (2020) that combined historical data and paleoclimate proxies with the process-based approach and yielded a best estimate of 3.1°C with a *likely* range of 2.6–3.9°C. Lewis (2022) raised a number of concerns about this result, including methodological errors, outdated input values, and use of subjective Bayesian priors in the analysis. Lewis' analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood *et al.* analysis – median 2.2°C (1.8–2.7°C in the 17–83 percent *likely* range, and 1.6–3.2°C in the 5–95 percent *very likely* range). The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis estimated it to be over 50 percent. The most recent publications on the debate between Sherwood *et al.* and Lewis further defend their respective positions: Sherwood and Foster (2024) and Lewis (2025).

An argument emphasized in AR6 is that data-driven ECS estimates might understate the future warming response to GHGs because of a so-called “pattern effect” (Forster *et al.*, 2021). The tropical Pacific is believed to strongly influence the overall efficiency with which the Earth radiates heat to space, but some regions remove heat more efficiently than others. If the west-to-east temperature gradient in the tropical Pacific is weakened in a warming climate, warming would concentrate where heat is less efficiently removed, raising ECS.

Most climate models simulate that rising GHGs will weaken the west-east temperature gradient, which led the IPCC in AR6 to conclude that data-driven ECS estimates understated the *future* ECS value. However, Seager *et al.* (2019) pointed out that, contrary to models, the west-east temperature gradient has been strengthening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterization of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee *et al.* (2024), who concluded that “the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere”; in other words, GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate might be *lower* than current estimates.

4.4 Transient Climate Response

The Transient Climate Response (TCR) provides a more useful observational constraint on climate sensitivity. TCR is the global temperature increase that results when CO₂ is increased at an annual rate of 1 percent over a period of 70 years (*i.e.*, doubled gradually). Relative to the ECS, observationally determined values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (*e.g.*, ice sheets). TCR is more generally related to peak warming and better constrained by historical warming, than ECS. IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C. In contrast to ECS, the upper bound of TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) are 1.25 to 2.0°C, showing much better agreement with AR6 values than was seen in a comparison of the ECS values.

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5 MODELS VERSUS OBSERVATIONS IN THE RECENT PAST

Chapter summary

Climate models show warming biases in many aspects of their reproduction of the past several decades. In response to estimated changes in forcing they produce too much warming at the surface (except in the models with lowest ECS), too much warming in the lower-and mid-troposphere and too much amplification of warming aloft.

Climate models also produce too much recent stratospheric cooling, invalid hemispheric albedos, too much snow loss, and too much warming in the Corn Belt. The IPCC has acknowledged some of these issues but not all.

5.1 Introduction

Climate models are the primary tool used to project future climate changes in response to increasing atmospheric levels of anthropogenic greenhouse gases. To assess the fitness of climate models for this purpose, it is reasonable to ask how well they reproduce the current climate and its variations over the past century. The box “Climate modeling” gives some detail on how climate models work.

Of great concern is the fact that, after several decades of the climate modeling enterprise involving approximately three dozen models operated by research centers around the world, the range of future warming they produce in response to a hypothetical doubling of atmospheric CO₂ extends over a factor of three, as we discussed in the previous chapter. This range of disagreement among models has not decreased for decades.

Problems with climate models are not just in their disagreement over the future, but also in their ability to replicate the recent past. Here we review some of the most important metrics of climate model accuracy: ability to reproduce historical surface, tropospheric and stratospheric temperature trends; ability to reproduce the vertical warming profile; and ability to reproduce other climate features such as snowfall. In all cases a persistent finding is that models on average err on the side of too much warming in response to estimated historical forcings.

BOX: Climate modeling

Most climate models, except for the simplest ones, represent Earth's land surface using a grid of squares on the order of 100 km wide. To simulate the atmosphere, typically 30 or more grid boxes are stacked above these squares. The ocean is modeled using a similar but finer grid, resulting in tens of millions of grid boxes for the atmosphere and oceans.

The computer models, based on physical laws, calculate how air, water, and energy move between grid boxes over time. The time step can be as small as 10 minutes, and repeating this process millions of times allows the simulation of climate over centuries. Running these models, even on the most powerful supercomputers, can take months. Comparing simulation results with historical climate data helps assess the accuracy of a model, while projections into the future estimate climate changes under assumed human and natural influences.

Despite sounding straightforward, climate modeling is highly complex. Many critical processes occur at scales smaller than the grid size. For instance, the flows of sunlight and heat in the atmosphere depend strongly on cloud cover. Since tracking individual clouds is impractical, researchers must make “subgrid” assumptions about the distribution of clouds in each grid box. Snow and ice cover, which affects how much sunlight is reflected or absorbed by the surface, is another subgrid factor.

Each subgrid assumption requires numerical parameters, which must be carefully set. Modelers initially estimate these parameters based on physics and observed climate patterns, then run the model. Because early results often diverge significantly from real-world observations, they “tune” these parameters to better match observed climate features. Different modeling teams use distinct assumptions and tuning strategies, leading to varied outcomes. Tuning is a necessary but delicate aspect of climate modeling, as it is for any complex system. Poor tuning can result in inaccurate simulations, while excessive tuning risks artificially steering results toward predetermined conclusions.

The spread of model representations of the current climate is very wide. One of the most basic indicators—Earth's average surface temperature—varies by about 3°C across CMIP6 models prior to 1880 (Figure 5.1), narrows slightly until 2040 then diverges to over 4 °C. For comparison 20th century warming was only about 1.0°C. This variation suggests substantial differences among models' physical processes.

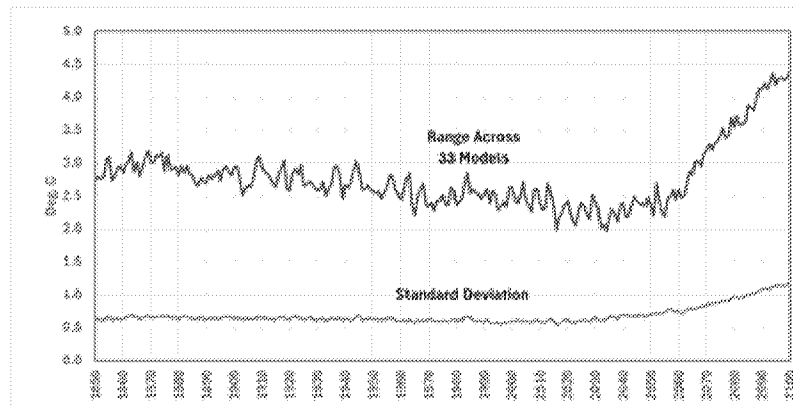


Figure 5.1 CMIP6 Average surface temperature range across 33 models and standard deviation using SSP5-85 scenario. Data from KNMI Climate Explorer website at [[HYPERLINK "https://climexp.knmi.nl/start.cgi"](https://climexp.knmi.nl/start.cgi) \t "_blank"].

Beyond the models' ability to reproduce features of today's climate, the critical issue for society is how well they predict responses to subtle human influences, such as greenhouse gas emissions, aerosol cooling, and land-use changes. The most crucial aspect that models must capture correctly is “feedbacks.” These occur when climate changes either amplify or suppress further warming. In general, the modeled net effect of all feedbacks doubles or triples the direct warming impact of CO₂.

5.2 Surface warming

A straightforward test of a climate model's validity is its ability to reproduce historical warming in response to known past changes in climate drivers such as greenhouse gases. Figure 5.2 is reproduced from Scafetta (2023), that groups the latest-generation (CMIP6) climate models into low ECS (1.5 to 3.0 degrees C), medium ECS (3.0 to 4.5 degrees C) and high ECS (4.5 to 6.0 degrees C), and compares their post-1980 global average temperature simulation ranges to those of three surface temperature records and one satellite-based lower troposphere temperature data product.

The leftmost column shows that the low-ECS models track the post-1980 historical warming record reasonably well, but the middle and right columns show that the medium- and high-ECS models conspicuously over-predict the warming.

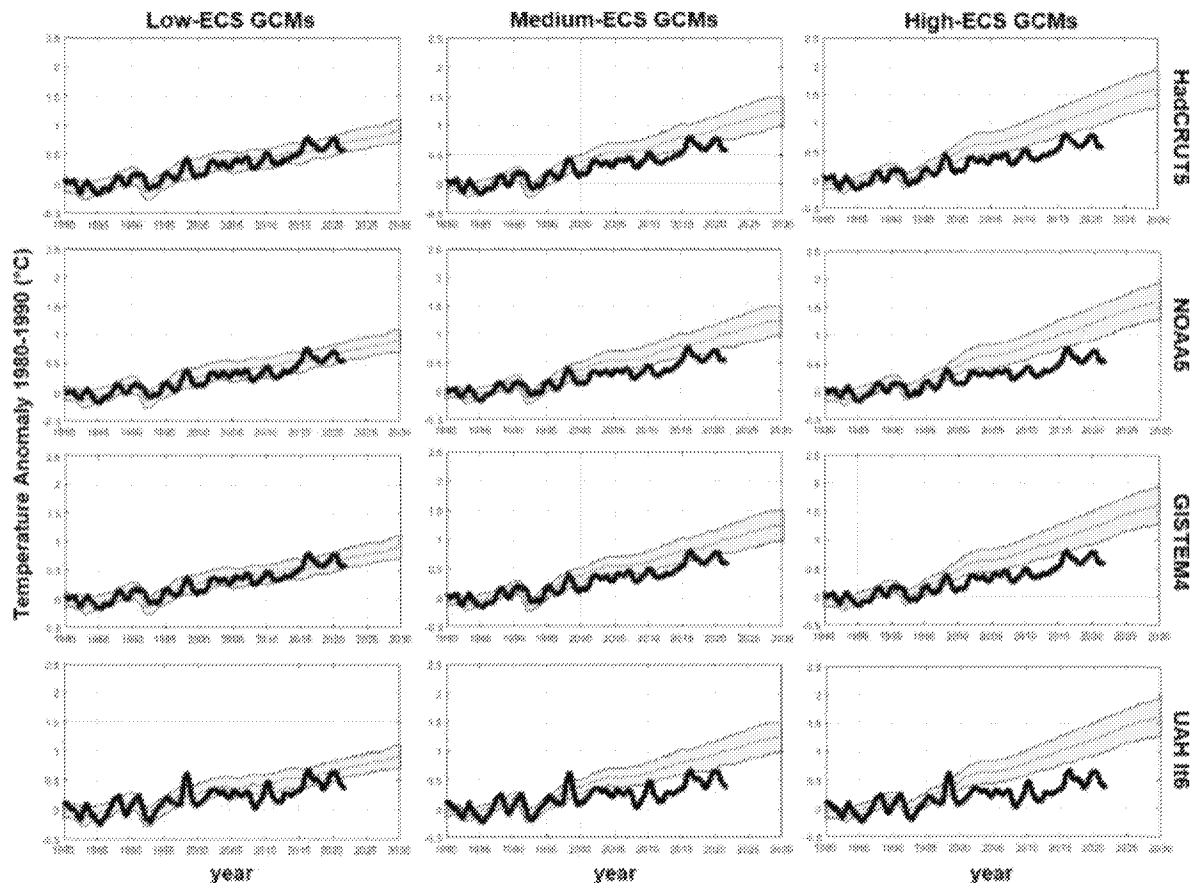


Figure 5.2: Model-Observational comparisons for Earth's surface warming. The columns correspond to model groups showing low-ECS to high-ECS, while the rows correspond to widely-used observed temperature records, the first three showing surface averages and the fourth showing the lower troposphere average. In each panel the yellow area denotes the mean and range ($\pm$ one standard deviation) of climate model simulations for that group. The thick black line shows the observed annual average temperature in the indicated source. Source: Scafetta (2023) Fig.2.

Spencer (2024) has also provided a useful summary of the Model-Observation mismatch by comparing trends in surface temperature data products with those in individual climate models, as summarized in Figure 5.3; most climate models show substantially more warming than the observations since 1979.

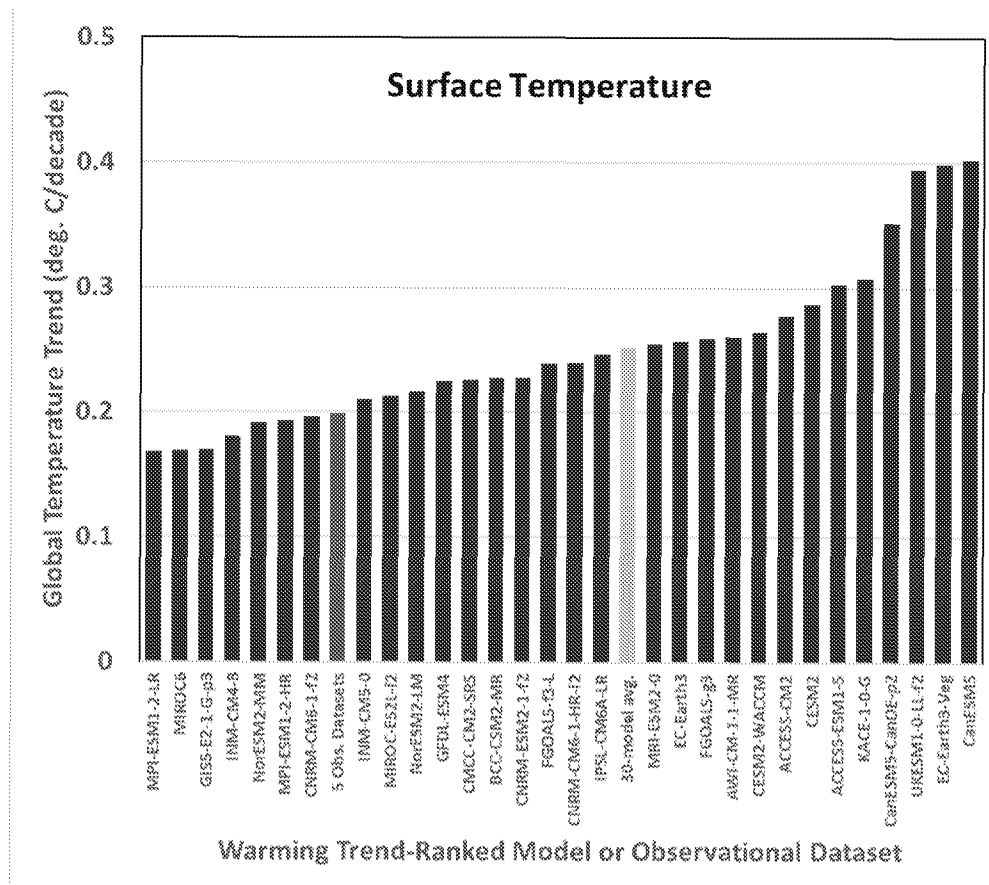


Figure 5.3 Global surface air temperature trends ($^{\circ}\text{C}/\text{decade}$), 1979-2024, from various CMIP6 climate models (red, 30-model average in orange); and the average of three thermometer datasets (HadCRUT5, NOAA Global Temp, and Berkeley 1 deg.) and two reanalysis datasets (ERA5 and NCEP/NCAR R1) in blue. Data source: <https://climexp.knmi.nl/start.cgi>.

5.3 Tropospheric warming

It has long been known that climate models on average overstate warming in the tropical troposphere. This region is an important test of climate models since this is where the signal of anthropogenic greenhouse warming emerges first and most strongly. Biases in tropospheric trends indicate model flaws in heat transfer processes that carry over to surface warming biases.

The discrepancy was flagged as a serious inconsistency in the first U.S. Climate Change Science Program report (Karl *et al.* 2006) and has been mentioned in every IPCC report since, but the discrepancy has gotten worse over time, and the bias is now global. McKittrick and Christy (2020) compared tropospheric warming trends in CMIP6 climate models to observed trends from satellites, weather balloons and reanalysis systems. Every model overpredicted the average observed warming trend over 1979-2014 in both Lower- and Mid-Troposphere layers, both globally and in the tropics. In most individual models the bias was statistically significant and on average across models it was highly significant.

Figure 5.4 presents the comparisons with data updated to 2024 (McKittrick and Christy 2025). The recent warm years moved the observed trend up slightly and widened the trend confidence intervals but the overall pattern remains the same: model bias is towards too much warming, in most cases the difference is statistically significant and on average the bias is statistically highly significant. McKittrick and Christy (2020) also showed that the bias is larger in high-ECS models, but even the models with lower average ECS predict too much warming. If future climate models were to realistically represent global tropospheric warming, they would likely be less sensitive than even the low-ECS members of the CMIP6 ensemble.

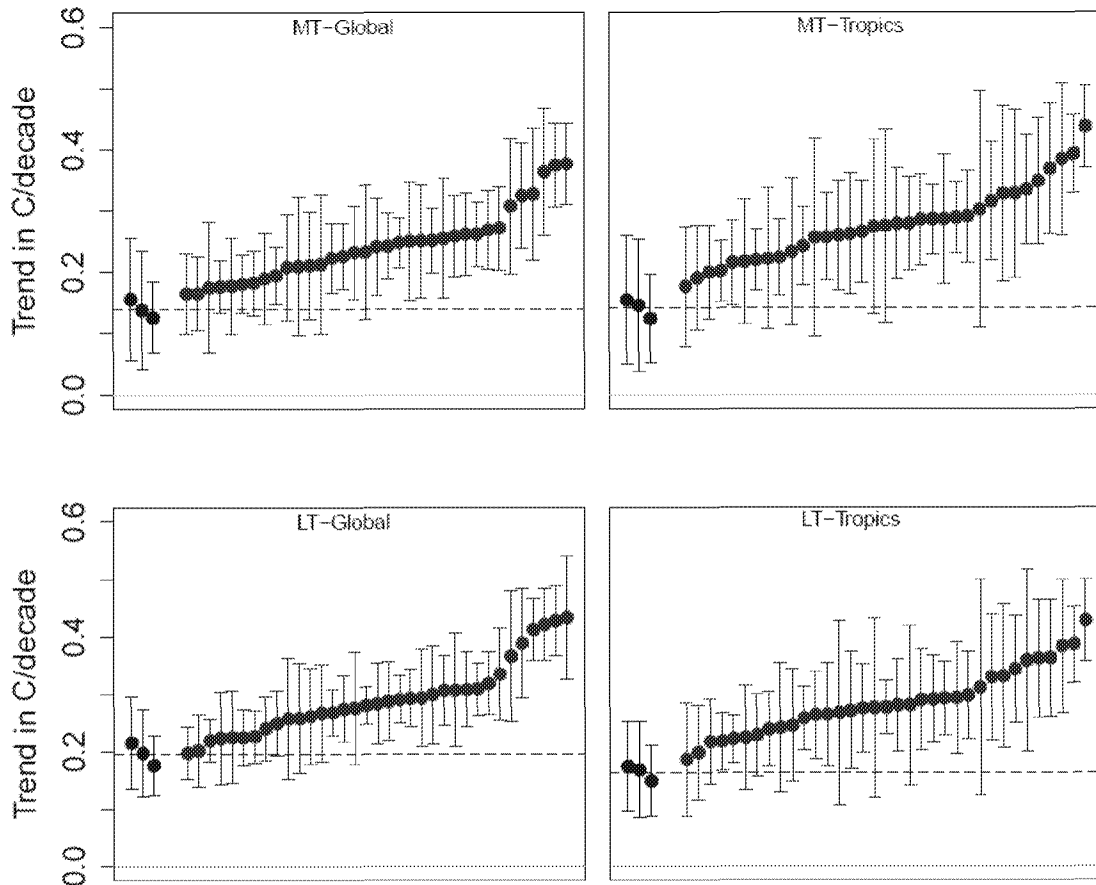


Figure 5.4: Observed versus CMIP6 modeled warming trends ($^{\circ}\text{C}/\text{decade}$ 1979-2024) in the global and tropical lower (LT) and mid-troposphere (MT). Uses methodology of McKittrick and Christy (2020) on data updated from 2014 to 2024. Blue dots: warming trends with 95 percent confidence intervals for 3 data products (radiosondes, reanalysis, and satellites). Blue dashed line: warming trend average for 3 observed series. Red dots: modeled warming trends with 95 percent confidence intervals in 35 models arranged lowest to highest.

As mentioned previously, the IPCC has long acknowledged the model-observation mismatch. For example, AR6 pp. 443-444 offers this on the tropical troposphere (it does not address the global comparison):

Several studies since AR5 have continued to demonstrate an inconsistency between simulated and observed temperature trends in the tropical troposphere, with models simulating more warming than observations (Mitchell *et al.*, 2013, 2020; Santer *et al.*, 2017a, b; McKittrick and Christy, 2018; Po-Chedley *et al.*, 2021)... Over the 1979–2014 period, models are more consistent with observations in the lower troposphere, and least consistent in the upper troposphere around 200 hPa, where biases exceed 0.1°C per decade. Several studies using CMIP6 models suggest that differences in climate sensitivity may be an important factor contributing to the discrepancy between the simulated and observed tropospheric temperature trends (McKittrick and Christy, 2020; Po-Chedley *et al.*, 2021), though it is difficult to deconvolve the influence of climate sensitivity, changes in aerosol forcing and internal variability in contributing to tropospheric warming biases (Po-Chedley *et al.*, 2021). Another study found that the absence of a hypothesized negative tropical cloud feedback could explain half of the upper troposphere warming bias in one model (Mauritsen and Stevens, 2015).

... In summary, studies continue to find that CMIP5 and CMIP6 model simulations warm more than observations in the tropical mid- and upper-troposphere over the 1979–2014 period (Mitchell *et al.*, 2013, 2020; Santer *et al.*, 2017a, b; Suárez-Gutiérrez *et al.*, 2017; McKittrick and Christy, 2018), and that overestimated surface warming is partially responsible (Mitchell *et al.*, 2013; Po-Chedley *et al.*, 2021). Hence, we assess with *medium confidence* that CMIP5 and CMIP6 models continue to overestimate observed warming in the upper tropical troposphere over the 1979–2014 period by at least 0.1°C per decade,

Notably, despite the accumulation of evidence of excess model warming the IPCC assigns only *medium confidence* to the existence of a warming bias.

5.4 Vertical temperature profile mismatch

Another important model-observational discrepancy is the excess amplification with altitude found in climate models. The comparison was in the IPCC AR5 Chapter 10, although only in the online supplement (Figure 10.SM.1) and only in a figure whose formatting obscured the point. Figure 10.SM.1 is not referenced in the main IPCC report nor in any summary so readers would not have been aware of it. Although not apparent at first glance, it shows that the 1979-2010 warming in the lower troposphere is so small as to be consistent with no GHG forcing at all and is inconsistent with the model runs that do have GHG forcing. In Figure 5.6 we adapt IPCC AR5 Figure 10.SM.1 to draw out this critical point.

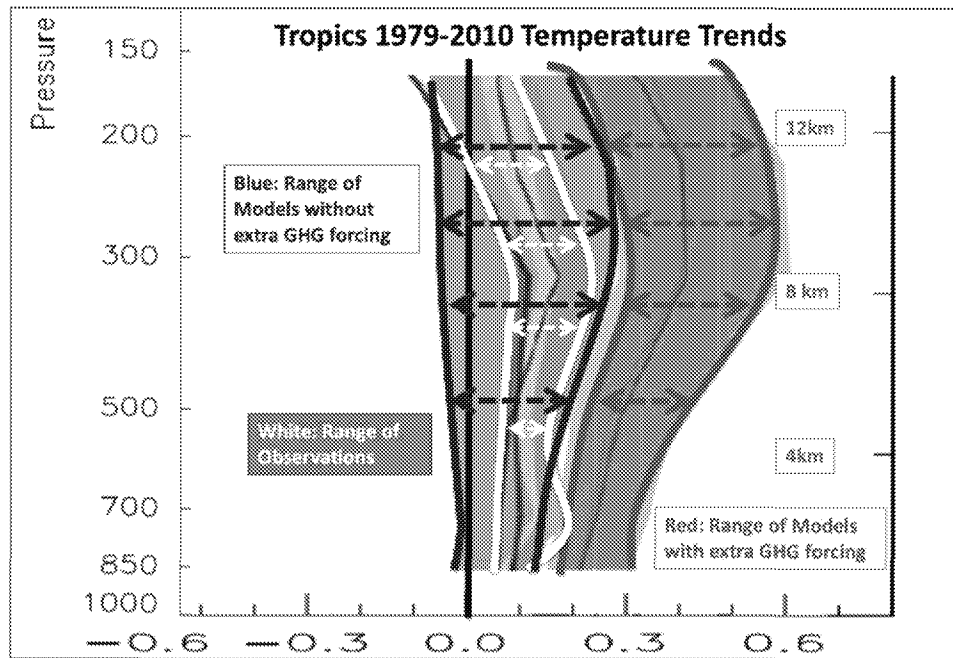


Figure 5.6: Vertical warming pattern for tropics (20S to 20N). Source: Annotated version of IPCC AR5 Figure 10.SM.1

Figure 5.6 compares model and observational temperature trends by altitude between 20S and 20N (the tropics). In this region where the models say the warming should be strongest, the observations (shown here in white) lie within the blue “No CO₂” band and entirely outside the “with CO₂” red envelope. This means that in the entire tropical atmospheric column from the surface to the base of the stratosphere, observed warming trends are so small as to be consistent with the output of models that have no anthropogenic CO₂, and inconsistent with the entire envelope of warming trends generated by models forced with increased CO₂.

A similar comparison is shown in Christy and McNider (2017), an updated version of which (covering 1979-2024) is reproduced as Figure 5.7. Modeled temperature trends exceed observations from the surface through the top of the troposphere, with observed trends below the entire model range at most pressure levels. Also shown in Figure 5.7 is the tropical tropospheric temperature (TTT) average from three satellite data products (NOAA, UAH and RSS) compared to the same layer average from climate models for 1979-2024. Again, the observed trends lie below the entire model range.

The wide range of choices made by modelers to characterize the physical processes in the models (see Box: Climate Modeling in Section 5.1 above) is seen by the large spread of trends in the middle troposphere, ± 40 percent about the median (Fig. 5.7). This vividly illustrates the uncertainties in attempts to model (parameterize) a complex system involving turbulence, moist thermodynamics, and energy fluxes over the full range of the tropical atmosphere’s time and space scales.

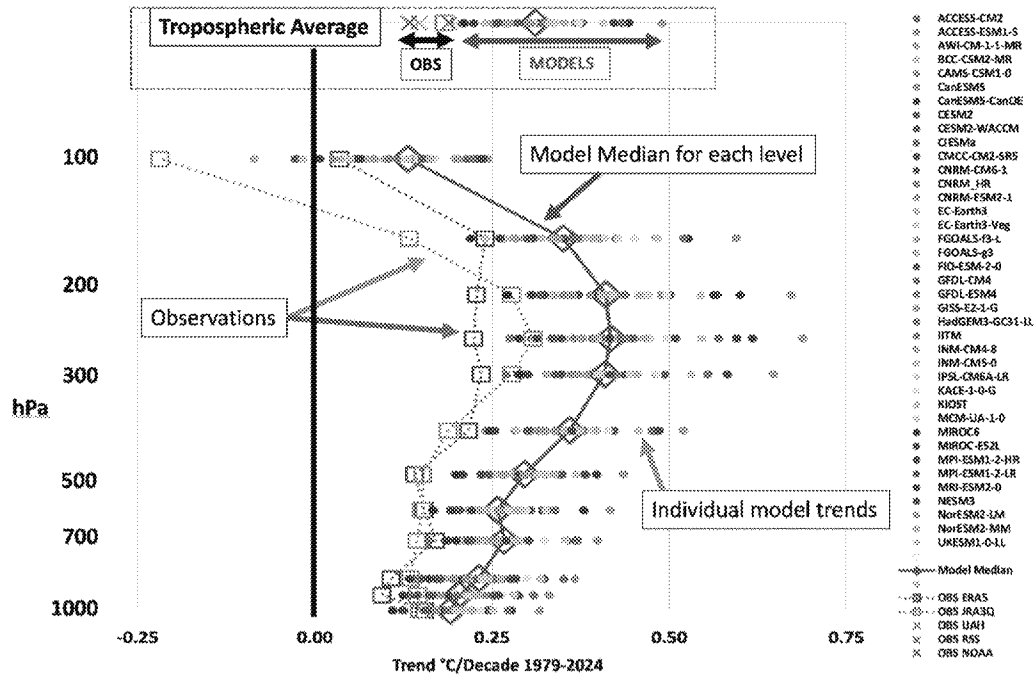


Figure 5.7: Modeled versus observed warming, tropical troposphere. Source: updated from Christy and McNider (2017) including data through 2024. Red line: model average. Green and blue lines: observational series (reanalysis).

This discrepancy has been the source of much controversy, with some arguing that even if there is very little observed warming aloft in the tropics, a “hotspot” still exists in the sense that the warming aloft is greater than at the surface (Santer et al. 2008). But there is good evidence that models also exaggerate the amplification rate. Klotzbach *et al.* (2009), showed that models project greater amplification with altitude than is observed. This result was subsequently confirmed by detailed time series analysis (Vogelsang and Nawaz 2016) which found that the model-observational difference is statistically significant.

The atmosphere’s temperature profile is a case where models are not merely uncertain but also show a common warming bias relative to observations. This suggests that they misrepresent certain fundamental feedback processes.

The IPCC AR6 did not assess this issue.

5.5 Stratospheric cooling

An important element of the expected general “fingerprint” of anthropogenic climate change is simultaneous warming of the troposphere and cooling of the stratosphere. AR6 acknowledged that cooling had been observed but only until the year 2000. The stratosphere has shown some warming since, contrary to model projections.

AR6 WG1 Ch 2 pp. 327-9 states:

Temperatures averaged through the full lower stratosphere (roughly 10–25 km) have decreased over 1980–2019 in all data products, with the bulk of the decrease prior to 2000. The decrease holds even if the influence of the El Chichon (1982) and Pinatubo (1991) volcanic eruptions on the trend,

found by Steiner *et al.* (2020a) to have increased the 1979–2018 cooling trend by 0.06°C per decade, is removed. Most datasets show no significant or only marginally significant trends over 2000–2019, and the results of Philipona *et al.* (2018) show weak increases over 2000–2015 in the very lowermost stratosphere sampled by radiosondes....

It is virtually certain that the lower stratosphere has cooled since the mid-20th century. However, most datasets show that lower stratospheric temperatures have stabilized since the mid-1990s with no significant change over the last 20 years. It is likely that middle and upper stratospheric temperatures have decreased since 1980, but there is low confidence in the magnitude.

The cited source, Philipona *et al.* (2018), in an article entitled “Radiosondes Show That After Decades of Cooling, the Lower Stratosphere Is Now Warming”, stated:

In response to continued greenhouse gas increases and stratospheric ozone depletion, climate models project continued tropospheric warming and stratospheric cooling over the coming decades. Global average satellite observations of lower stratospheric temperatures exhibit no significant trends since the turn of the century. In contrast, an analysis of vertically resolved radiosonde measurements from 60 stations shows an increase of lower stratospheric temperature since the turn of the century at altitudes between 15 and 30 km and over most continents. Trend estimates are somewhat sensitive to homogeneity assessment choices, but all investigated radiosonde data sets suggest a change from late twentieth century cooling to early 21st century warming in the lower stratosphere.

A combination of tropospheric warming and stratospheric cooling is a commonly cited “fingerprint” of anthropogenic warming. Stratospheric warming since 2000 coincides with continued surface and tropospheric warming, a pattern that is not found in climate model simulations and is not apparently consistent with the anthropogenic fingerprint.

5.6 Snow cover mismatch

Data compiled by the Rutgers University Snow Lab show that Northern Hemisphere winter snow cover is not decreasing (Figure 5.8); if anything, it shows an increasing trend.

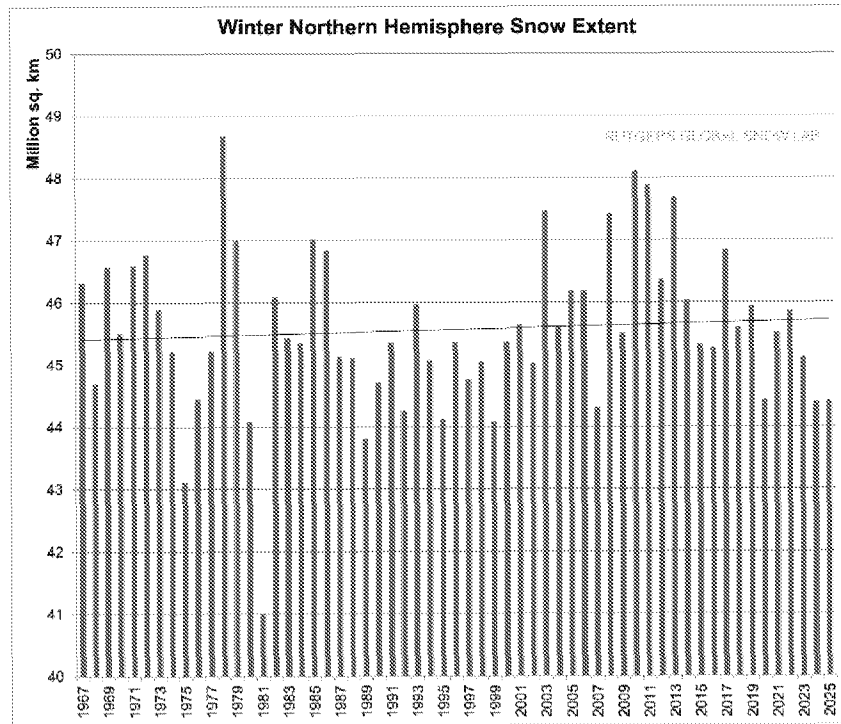


Figure 5.8: Northern Hemisphere Winter Snow extent.

Source: [[HYPERLINK](https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhland&ui_season=1)]

"https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhland&ui_season=1"]
(accessed May 27, 2025)

Yet models project declining Northern Hemisphere snow cover in a warming climate, as described by Connolly *et al.* (2019).

The climate models were found to poorly explain the observed trends [in Northern Hemisphere snow cover]. While the models suggest snow cover should have steadily decreased for all four seasons, only spring and summer exhibited a long-term decrease, and the pattern of the observed decreases for these seasons was quite different from the modelled predictions. Moreover, the observed trends for autumn and winter suggest a long-term increase, although these trends were not statistically significant.

AR6 largely confines its discussion of changing Northern Hemisphere snow cover extent (SCE) to the Spring season, for which models and observations agree on a downward trend. Regarding Winter changes it remarks as follows (AR6 WGI Ch. 2 p. 344):

Assessment of SCE trends in the NH since 1978 indicates that for the October to February period there is substantial uncertainty in trends with the sign dependent on the observational product. Analysis using the NOAA Climate Data Record shows an increase in October to February SCE (Hernández-Henríquez *et al.*, 2015; Kunkel *et al.*, 2016) while analyses based on satellite borne optical sensors (Hori *et al.*, 2017) or multi-observation products (Mudryk *et al.*, 2020) show a negative trend for all seasons.

AR6 WGI Chapter 9 (p. 1284) points out that the NOAA Climate Data Record showing increased fall and winter SCE is inconsistent with land-based observations and model-based data sets. It notes that using optical satellite imagery to infer SCE in winter is challenging due to cloud cover and decreased solar illumination in winter months. Focusing on the Pacific Coast states (CA, OR and WA) cold season mountain snowfall that melts in spring and summer provides a substantial portion of warm season water resources. A comprehensive reconstruction of snowfall for the main source regions (Cascades and Sierra Nevada Mountains) indicates no significant trends in annual totals since the late 19th century (Christy 2022).

In summary, the up-to-date Rutgers SCE database indicates a mismatch between models and observations. Further work to reconcile conflicting trends in observational data sets is required.

5.7 Hemispheric symmetry of the planetary albedo

The planetary albedo is the fraction of incoming solar radiation reflected by the Earth back to space. It is an important element of the radiative energy balance and influences whether the planet will warm or cool over time. The planetary albedo is typically estimated at around 0.30; variations on the scale of 0.01 correspond to changes in solar forcing of about 3 W/m^2 , an amount larger than current anthropogenic forcing. It has long been noted that models disagree with each other and with observations on the value of the global planetary albedo (Stephens *et al.* 2015).

An intriguing property of the Earth's albedo is that, on average, the Northern Hemisphere (NH) and Southern Hemisphere (SH) have had nearly the same albedo, at least throughout the fifty-year satellite record (Stephens *et al.*, 2015). This symmetry is surprising, because the SH has much more ocean than land. Since ocean is less reflective than land, the NH should have higher albedo. Clouds (which are highly reflective) are more common in the NH and so compensate the surface albedo imbalances of the two hemispheres. Datseris and Stephens (2021) show that this cloud compensation comes from the extra-tropical storm tracks of the SH, which are cloudier than those of the NH. While the mechanism for this hemispheric symmetry is unclear, it likely operates on large temporal and spatial scales.

The hemispheric symmetry of the albedo is a simple gross metric for climate models. Rugenstein and Hakuba (2023) defined that metric as the difference between the NH and SH annual mean albedos, expressed as Wm^{-2} of the reflected sunlight, and compiled it for the CMIP6 climate models, as shown in Figure 5.9. Most of the CMIP6 models do not reproduce the small observed asymmetry (about 0.1 Wm^{-2}) and even disagree as to which hemisphere is more reflective. Moreover, the magnitude of the asymmetry ranges up to 5 Wm^{-2} in some models, twice as large as the current anthropogenic forcing (about 2.5 Wm^{-2}).

The significance of unphysical albedo asymmetries in the climate models is not yet fully known. However, other model studies suggest that interhemispheric changes in albedo can alter poleward heat fluxes, meridional temperature gradients, storminess, and differences in hemispheric ocean heat storage. The discrepancy between models and observations further raises issues regarding cloud feedback processes and so more generally diminishes confidence in model projections of the future climate.

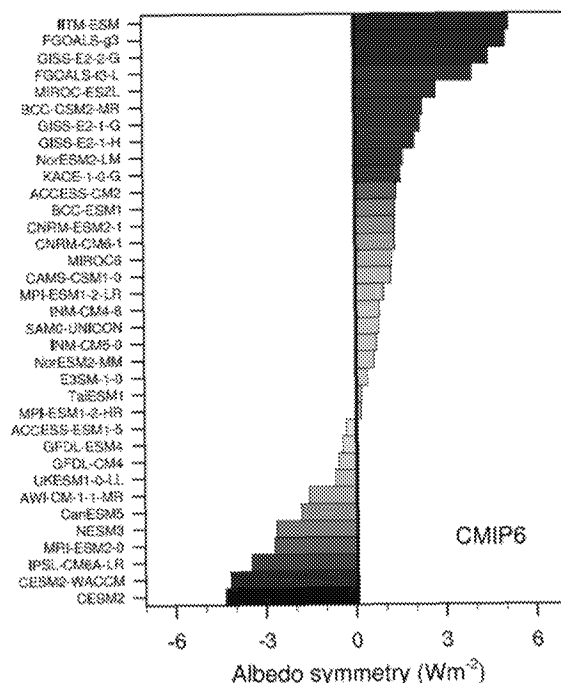


Figure 5.9. Differences in 20-year average reflectivity (albedo) between the Northern and Southern Hemispheres for CMIP6 models used in the most recent IPCC assessment (colored bars). The very small observed difference is indicated by the vertical black line. From Rugenstein and Hakuba (2023).

5.8 U.S. Corn Belt

One of the largest discrepancies between models and observations is in the U.S. Corn Belt, a region of particular importance to global food production. Figure 5.10 shows the warming trends for summertime (June, July, August) for the 12-state Corn Belt (IN, IA, IL, ND, SD, MO, MN, WI, MI, OH, KS, NE) during 1973-2022. All 36 climate models (red) warm far too rapidly compared to observations (blue).

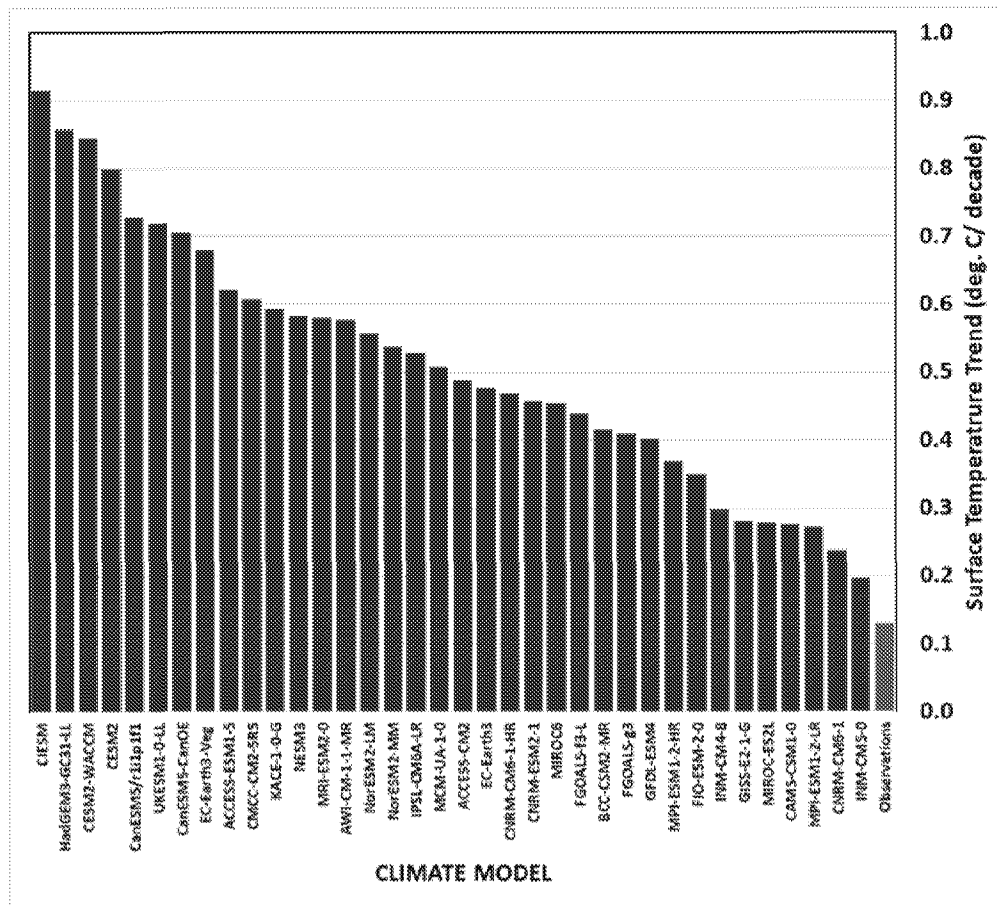


Figure 5.10: Modeled versus observed warming trends in the U.S. Corn Belt, 1973-2022.

As discussed in Chapter 9, the anticipated negative effects of increasing temperatures on U.S. corn yields have not materialized, in contrast to widely publicized studies proclaiming that theoretical future impacts are already being experienced (*e.g.*, Seager *et al.*, 2018).

The IPCC acknowledges limitations in the accuracy of regional climate model outputs. This example shows that users need to assess model projections carefully on a case-by-case basis since local biases might be sufficiently large that the models are simply not fit for purpose. As has recently been noted by two leaders of the modeling community (emphasis added)

... for many key applications that require regional climate model output or for assessing large-scale changes from small scale processes, we believe that **the current generation of models is not fit for purpose**. (Palmer and Stevens 2019)

To summarize:

- Climate models show warming biases in many aspects of their reproduction of the past few decades.
- They produce too much warming at the surface (except in the models with lowest ECS), too much warming in the lower-and mid-troposphere and too much amplification of warming aloft
- They also produce too much stratospheric cooling, too much snow loss, and too much warming in the U.S. Corn Belt.

- The hemispheric albedo difference in individual climate models ranges widely in sign and magnitude compared to observations. The range in W/m^2 is three times larger than the direct anthropogenic forcing of CO_2 .
- The IPCC has acknowledged some of these issues but not others.

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6 EXTREME WEATHER

Chapter Summary

Most types of extreme weather exhibit no statistically significant long-term trends over the available historical record. While there has been an increase in hot days in the U.S. since the 1950s, a point emphasized by AR6, numbers are still low relative to the 1920s and 1930s. Extreme convective storms, hurricanes, tornadoes, floods and droughts exhibit considerable natural variability, but long-term increases are not detected. Some increases in extreme precipitation events can be detected in some regions over short intervals but the trends do not persist over long periods and at the regional scale. Wildfires are not more common in the U.S. than they were in the 1980s. Burned area increased from the 1960s to the early 2000's, however it is low compared to the estimated natural baseline level. U.S. wildfire activity is strongly affected by forest management practices.

6.1 Introduction

High impact weather extremes, usually related to temperature, precipitation and/or high wind, can disrupt infrastructure and therefore endanger human health and wellbeing. The issue is not whether extremes occur. Rather, it is whether there are long-term (decadal scale) changes in the frequency or character of extremes (“detection”), as well as the extent to which such changes and the attendant changes in hazards are caused by anthropogenic emissions of greenhouse gases (“attribution”; e.g., AR6 Seneviratne *et al.* 2021).

It is naïve to assume that any recent extreme event is caused by human influences on the climate. Climate is about the statistical properties of weather over decades, not single events. Further, there are only about 130 years of reliable observational records that can be analyzed statistically. That brief interval does not begin to contain all the extreme events that the climate system can create on its own. Over geologic time the climate system has generated an (essentially) infinite variety of weather patterns and extremes that humans have never observed and thus are absent from the databases used to determine extreme statistics [see *Perils of short data records* below]. For that reason, attributing an extreme event unprecedented in the record requires assumptions about the magnitude of natural variations.

This chapter is concerned with detection of trends in extreme weather, while Chapter 8 considers causal attribution, with Section 8.4 specifically addressing extreme weather. If no trend is detected, then clearly there is no basis for attribution. But even where a trend is observed, attribution to human-caused warming does not necessarily follow.

This is especially true for precipitation events. The hydrological literature has long noted the phenomenon of Long-Term Persistence (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2016). LTP has a formal mathematical definition, but it can be thought of as the presence of natural variations with strong autocorrelations that result in cycle-like behavior on long time scales. The presence of LTP requires long records to accurately estimate variability. Analysis of records that are short relative to the LTP scale will tend to underestimate variability, therefore overstating the significance of apparent trends and underestimating the likelihood of extreme events (Cohn and Lins 2005).

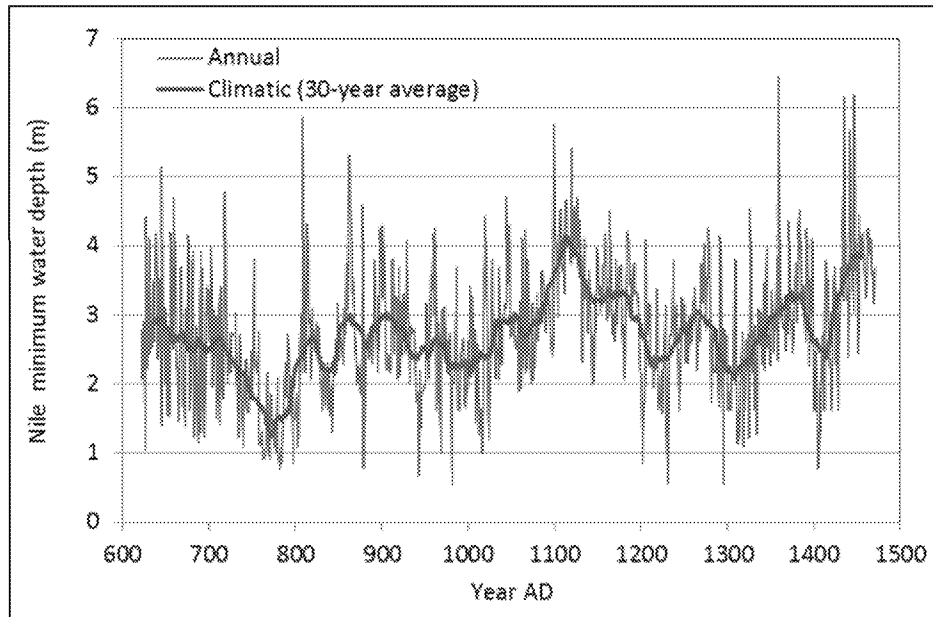


Figure 6.1.1: The annual minimum depth of the Nile River near Cairo over more than 650 years from 622 to 1284 A.D. The data, measured in meters, shows a characteristic pattern of year-to-year fluctuations around longer-term trends. Data from Koutsoyiannis (2013)

A good example of LTP is the eight-century long record of the annual minimum height of the Nile River observed at Roda Island in Cairo shown in Figure 6.1.1. The Nile River is fed by precipitation over a 4 million square mile drainage basin, an area equal to about one third of CONUS. Since human influences on the global climate were negligible before the 20th century, the century-scale variability of the thirty-year average is entirely natural; Egyptians of the seventh and eighth centuries would have been incorrect to assume that the worsening drought during that time was the “new normal.”

With these caveats in mind, we examine the evidence for changes in selected weather and climate extremes. A recurring theme is the wide gap between public perceptions and scientific evidence. It has become routine in media coverage, government and private sector discussions, and even in some academic literature to make generalized assertions that extreme weather of all types is getting worse due to GHGs and “climate change.” Yet expert assessments typically have not drawn such sweeping conclusions and instead have emphasized the difficulty both of identifying specific trends and establishing a causal connection with anthropogenic forcing.

In the sections to follow we provide excerpts from various IPCC and NCA assessment reports denoting the sources as follows:

SREX: The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2012)

AR6: The IPCC Sixth Assessment Report Working Group 1 (2021).

NCA4: The U.S. Climate Science Special Report of the Fourth National Climate Assessment (2017) Volume I.

NCA5: The U.S. Climate Science Special Report of the Fifth National Climate Assessment (2023) Volume I.

In the excerpts, *italics* are in the original whereas **boldface** emphasis has been added.

Additionally we present updated data series from standard government sources to provide up-to-date information through 2024 wherever possible.

6.2 Hurricanes and tropical cyclones

AR6 provides the following assessment of tropical cyclones (TCs; used here as a synonym for hurricanes):

AR6: There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (IPCC, 2021 p. 1585)

AR6: It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades . . . There is *low confidence* in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. (IPCC, 2023 SPM p. 9)

AR6: A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows **no trend in the frequency of U.S. landfall events**. (IPCC 2021 p. 1585)

Since 1980, when satellite observations first fully covered the global oceans, we have confidence in the numbers of total global hurricanes and major hurricanes (Category 3 and higher). Figure 6.2.1 shows that on average, each year there are about 50 hurricanes, with about 25 reaching major hurricane status (Maue, 2025). There is substantial year-to-year and decadal variability, a weak decrease in the number of hurricanes, and a slight but insignificant increase in the number of major hurricanes. These two trends combine to create an overall increase in the proportion of major hurricanes.

Global hurricane statistics are dominated by the Northwest Pacific Ocean, which accounts for ~35 percent of total global hurricanes, whereas the Atlantic accounts for ~15 percent of global hurricanes (Colorado State University, 2025). Data in the Atlantic basin extends further back than in the other ocean basins and is most relevant to U.S. policy makers.

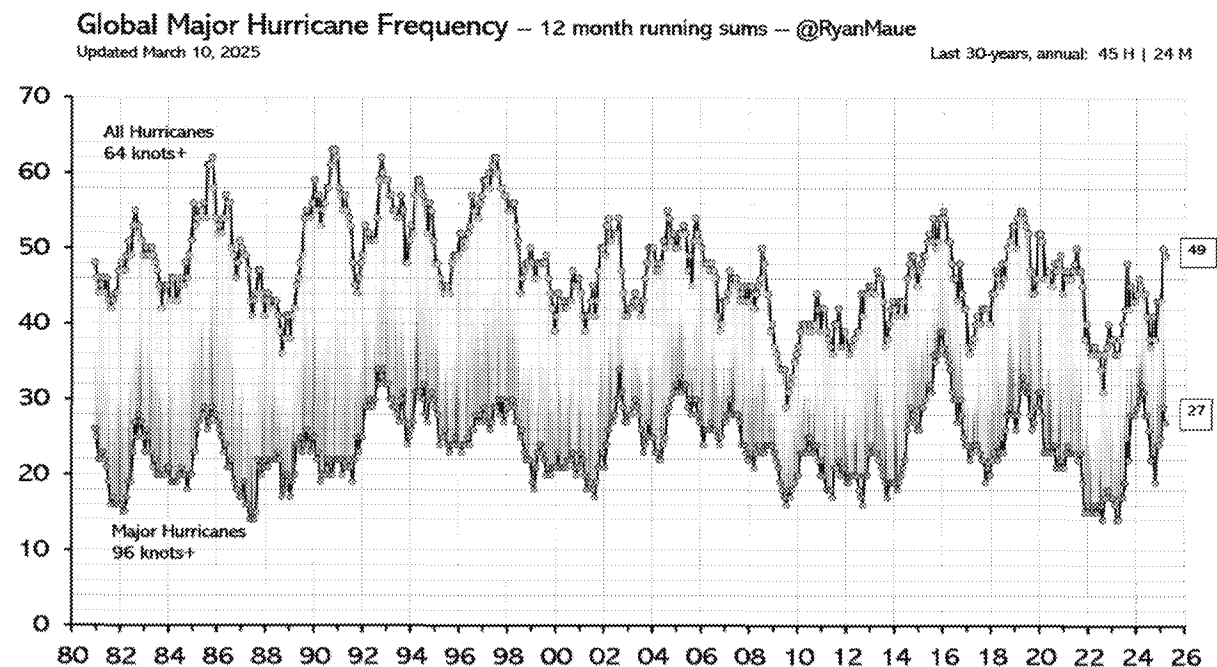


Figure 6.2.1: Global frequency of hurricanes and major hurricanes since 1980.

Figure 6.2.2 shows the frequency of Atlantic hurricanes and major hurricanes (Category 3 and higher) back to 1920. Data prior to 1965 (the onset of satellite observations in the Atlantic, shaded in blue) shows some undercounting, with data prior to 1920 showing substantial undercounting (Vecchi and Knutson, 2011). All measures of Atlantic hurricane activity show a significant increase since 1970. However, the period from 1971-1994 saw exceptionally low activity, with high activity (comparable to the past two decades, even with undercounting) also observed during the 1950's and 1960's, and even in the 1930's.

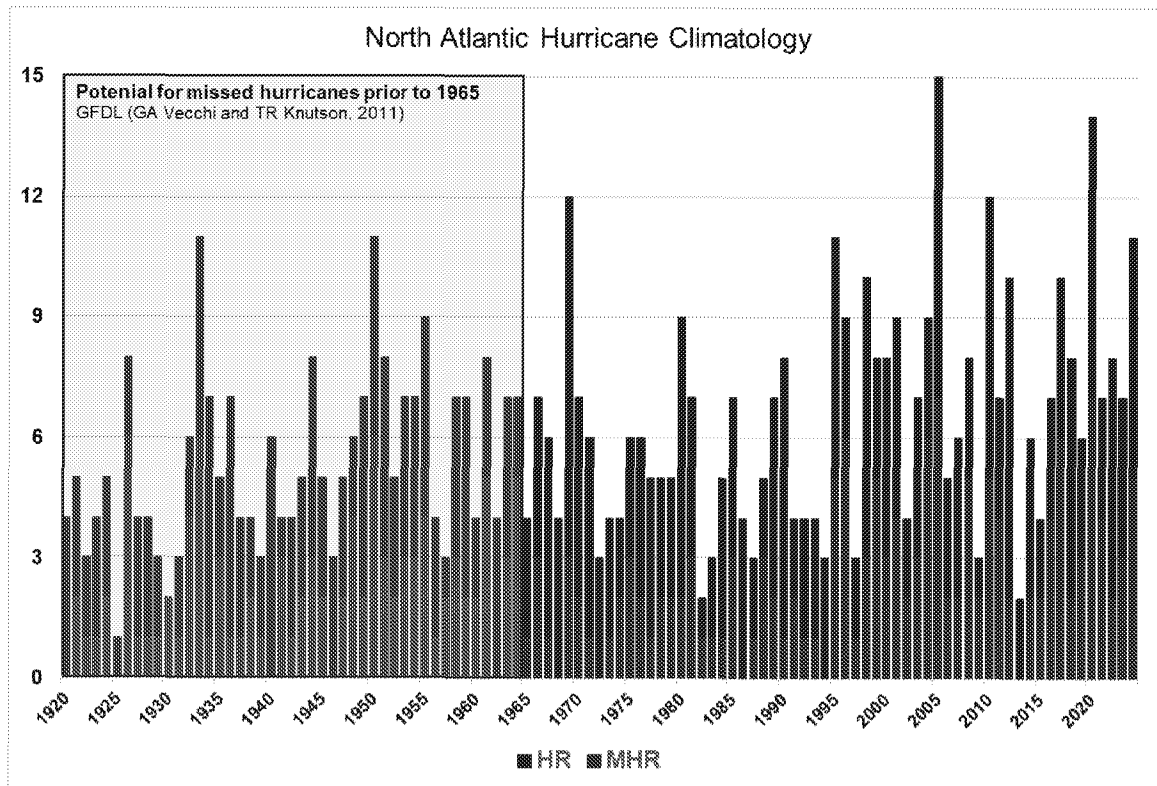


Figure 6.2.2: Atlantic frequency of hurricanes (HR) and major hurricanes (MHR) since 1920. Source National Hurricane Center (2024)

Figure 6.2.2 shows that Atlantic hurricanes vary strongly on decadal and multidecadal time scales. These variations are associated primarily with the Atlantic Multidecadal Oscillation (AMO), which is manifest in basin-wide sea surface temperature and sea level pressure fluctuations connected to large scale ocean circulation patterns. The AMO was in its warm phase during 1926-1970 and 1995-present, but in its cool phase during 1971-1994. It has its greatest impact on the number of major hurricanes (Category 3+), identified by Goldenberg *et al.* (2001) as associated with above normal SSTs and decreased vertical shear in the AMO warm phase (see also Bell and Chelliah, 2006; Klotzbach *et al.*, 2018).

Klotzbach *et al.* (2018) conducted a comprehensive evaluation of the landfalling hurricane data for the Continental U.S. since 1900. Figure 6.2.3 updates their analysis through 2024. While the largest numbers of landfalling hurricanes are from 2004, 2005 and 2020, there is no statistically significant trend since 1920. Figure 6.2.3 also shows the time series for major hurricane landfalls (Category 3-5). The largest year in the record is 2005, with 4 major hurricane landfalls. However, following 2005 there were no major hurricanes striking the U.S through 2016, the longest such period since 1920.

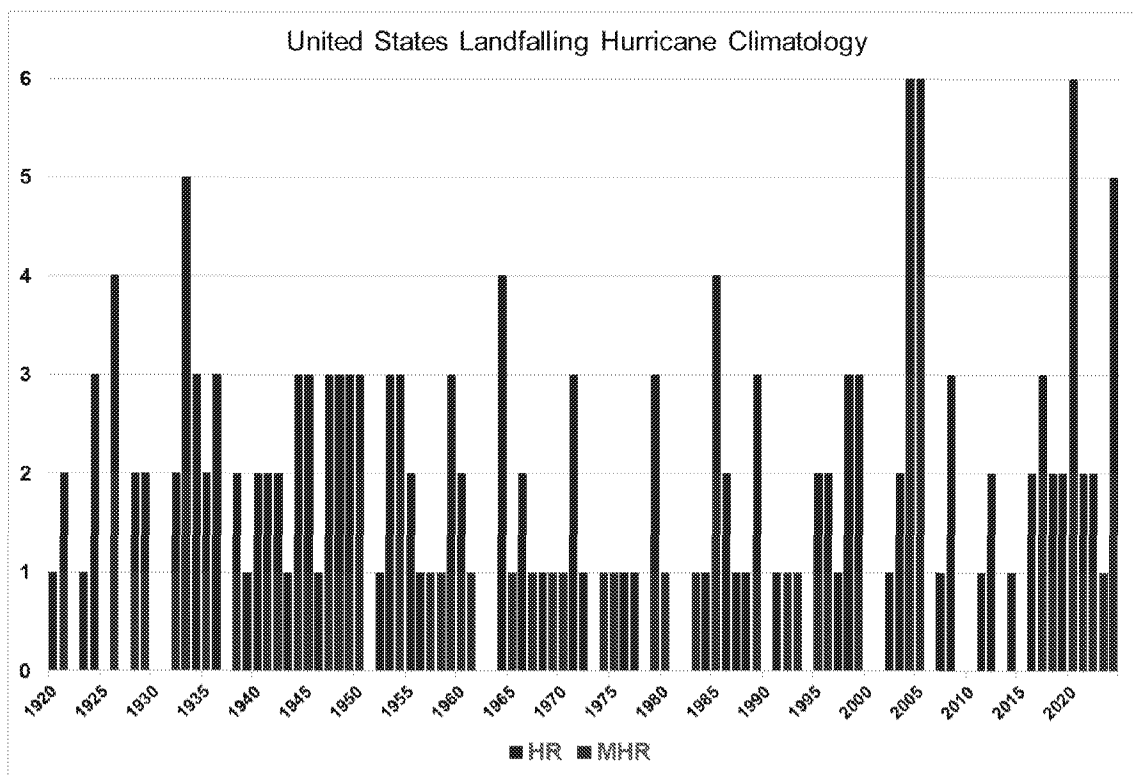


Figure 6.2.3: U.S. landfalling frequency of hurricanes (HR) and major hurricanes (MHR) since 1920. Source NOAA HRD(a) (2024)

Figure 6.2.3 shows substantial interannual to multidecadal variability in U.S. landfall activity. Klotzbach *et al.* (2018) examined how the landfall counts vary with ENSO (El Niño versus La Niña) and the warm versus cold phases of the Atlantic Multidecadal Oscillation (AMO).

Villarini *et al.* (2012) provide an analysis of U.S. hurricane landfalls back to 1878. While it is possible that some landfalls were missed in the late 19th century owing to sparsely populated regions on the Gulf Coast, it is remarkable that the highest year in the entire record is 1886, with 7 hurricane landfalls, when human influences on the climate were much smaller than they are today.

Table 6.2.1 shows the 10 strongest hurricanes (plus ties) to make U.S. landfall. Of the hurricanes that have made landfall with sustained winds greater than 150 mph, only one has occurred in the 21st century.

In summary, analyses of both global and regional variability and trends of hurricane activity provide the basis for detecting changes and understanding their causes. The relatively short historical record of hurricane activity, and the even shorter record from the satellite era, is not sufficient to assess whether recent hurricane activity is unusual relative to the background natural variability. Atlantic hurricane processes are influenced substantially by the natural modes of ocean circulation variability in the Atlantic, notably the Atlantic Multidecadal Oscillation. While it has long been hypothesized that a rising global sea surface temperature would cause an increase in hurricane intensity, identification of any significant trend in the hurricane data is hampered by a short data record and substantial natural variability.

Rank	Year	Landfall Wind (MPH)	Name
1	1935	185	"Labor Day"
2	1969	175	Camille
3	1992	165	Andrew
4	2018	160	Michael
5	1856	150	"Last Island"
5	1886	150	"Indianola"
5	1919	150	-----
5	1932	150	"Freeport"
5	2004	150	Charley
5	2020	150	Laura
5	2021	150	Ida
5	2022	150	Ian

Table 6.2.1 Strongest hurricanes to make landfall along the U.S. coast. Source (NOAA HRD(b), 2024)

6.3 Temperature extremes

The AR6 assessment focused on the period after 1950 and reported increasing trends in heatwave frequency and intensity. However, NCA4 noted that heatwave activity in the U.S. reached a peak in the 1930s (Figure 6.3.1).

AR6: It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe (SPM, A3.1)

AR6: In North America, there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, while there are more contrasting trends in the annual maximum daily temperatures in parts of the USA. (Chapter 11, p 1550)

NCA4: Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year **increased** in some parts of the West over the past century, but there were **decreases** in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net **decrease**, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). (pp. 190-191)

NCA4: Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, **heat wave magnitude reached a maximum in the 1930s.** (pp. 190-191)

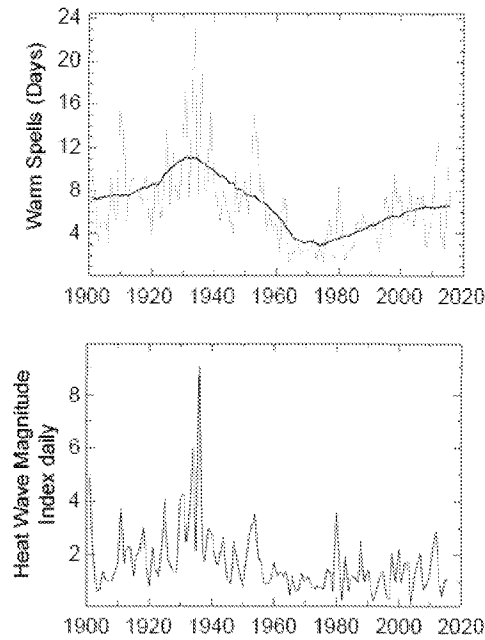


Figure 6.3.1: U.S. Heat waves since 1900. Source: NCA4 Figure 6.4

6.3.1 *Temperatures in the U.S. are becoming less extreme*

Daily maximum temperatures in the warm season (Tmax, May-Sep) and daily minimum temperatures in the cold season (Tmin, Dec-Mar) are available beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (see Figure 6.3.2; Quinlan *et al.* 1987, Karl *et al.* 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves, and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors in the dataset, including unresolved spurious warming due to UHI effects that especially bias Tmin records, this data set is sufficiently accurate for assessing trends in Tmax heat extremes.

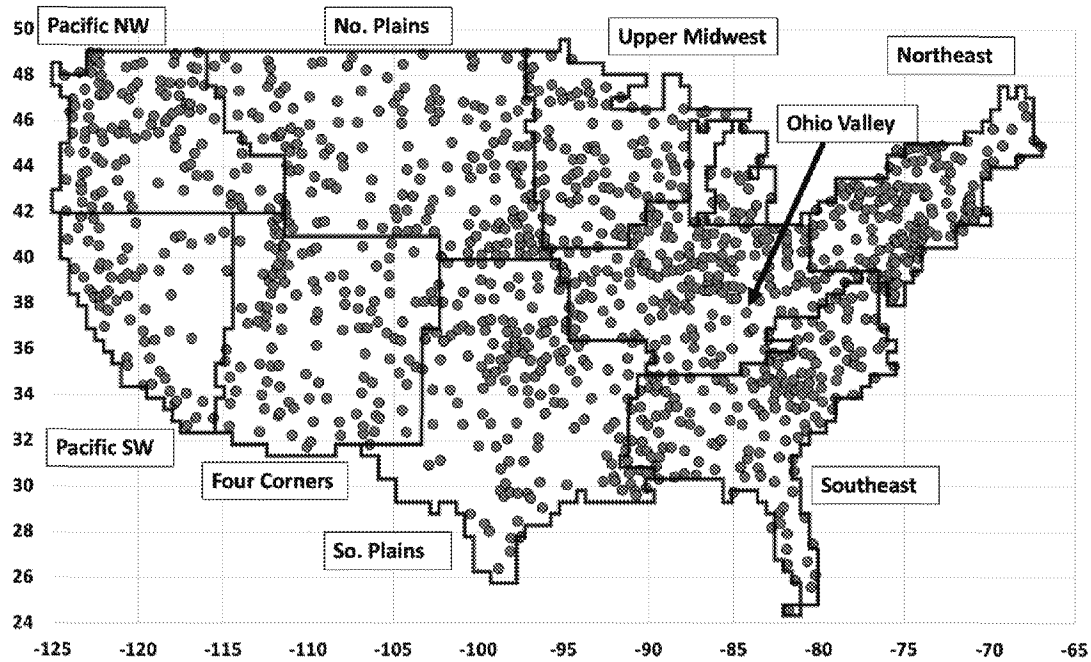


Figure 6.3.2 Locations of USHCN temperature stations. Source: USHCN.

We begin with the question of whether the occurrence of daily record high or low temperatures has changed since Dec 1898. Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each station and day, we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for Tmax would be 1.21 ($=153/126$) per station per year and for Tmin 0.96 ($=122/126$) per station per year.

Figure 6.3.3 shows the observed distribution in time of the occurrence of these extreme events. There is a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60 percent of the Tmax records and 59 percent of the Tmin records occurred in the first half of the period (1899-1961).

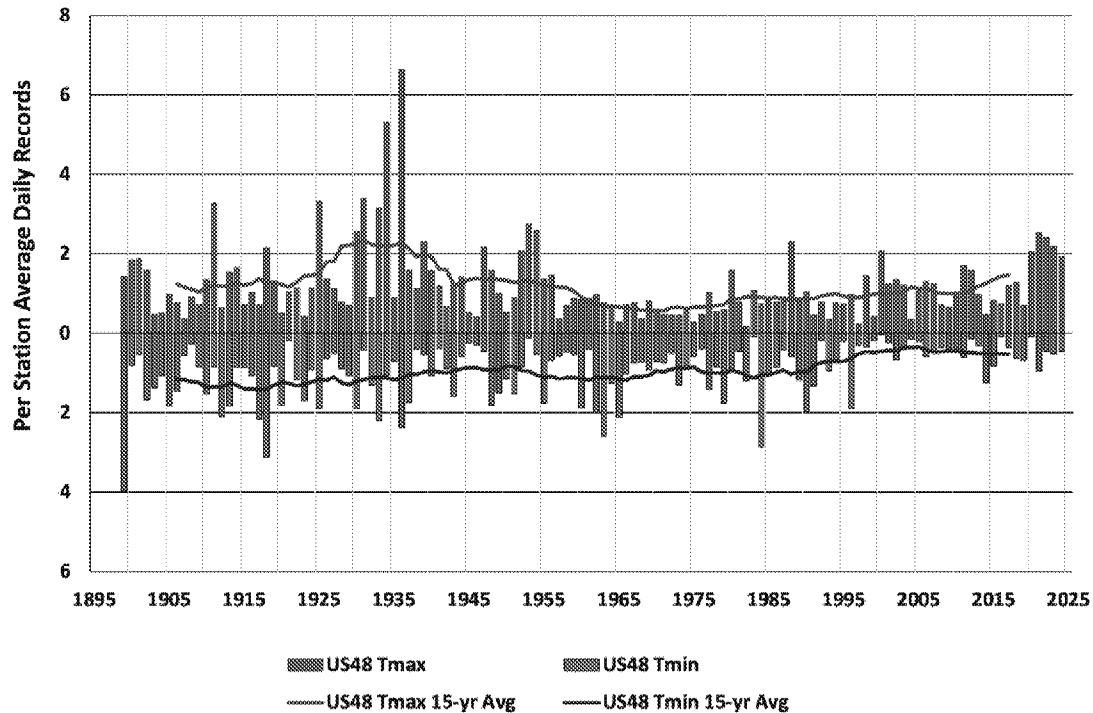


Figure 6.3.3 Number of daily record High (red) and Low (blue) temperatures for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92 percent of observations in the 126-year period since Dec 1898. US48: contiguous U.S. states. Tmax: maximum temperature. Tmin: minimum temperature.

On the cold side, the Valentine’s Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced by CONUS, with 1917 in 2nd place. The frequency of cold records has declined, especially over the last quarter of the period in which only 13 percent of the extreme cold events were measured. In contrast, 25 percent of the extreme Tmax records were achieved in the last quarter, in accordance with statistical expectations. These general features have been noted in past assessments (see above, IPCC AR6, NCA4). Combining the two histories, the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 6.3.4. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated. Then the differences between these were computed by station and geographically-averaged over all stations, thus yielding an annual measure of the expected range of local extreme temperatures for each year. Figure 6.3.4 shows the 15-year trailing average of this measure, which has clearly declined over the past century.

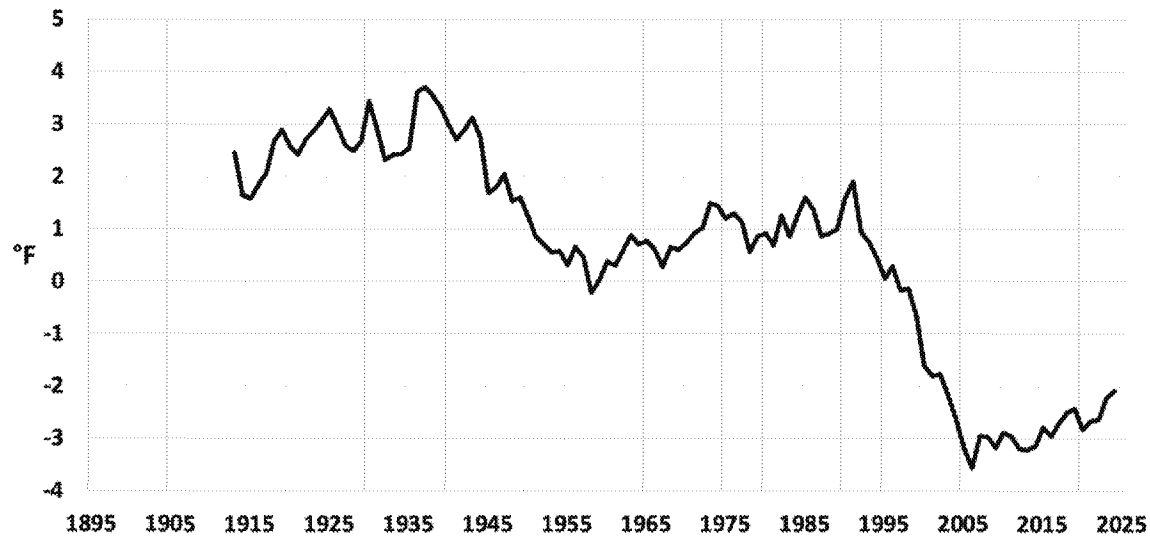


Figure 6.3.4. 15-year trailing average of the difference each year of each station's hottest warm-season Tmax and coldest cold-season Tmin relative to the long-term average. Source: Author analysis of USHCN data.

The average difference for each station between the hottest summer Tmax and coldest winter Tmin has declined by about 5°F in the past 126 years. The decline is due mostly to warmer winter Tmin, but a decline in summer Tmax is also a factor. The rise in Tmin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (the so-called urban heat island effect; Section 3.3 and Spencer *et al.* 2025).

In summary, while temperature extremes are regularly experienced in the U.S. and attract a great deal of media attention, long term records show the U.S. climate has become less extreme over time (milder) when measured by the range between warm season maxima and cold season minima.

6.3.2 Exceedances of a heat threshold

Under the heading of “The Risk of Temperature Extremes is Changing”, the most recent U.S. National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating,

The western U.S. has been particularly affected by extreme heat since the 1980s ..., experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the U.S. since 2018, including a record-shattering event in the Pacific Northwest in 2021.

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations that have near 95°F Tmax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F Tmax temperatures, a small change will not have much impact on the results.

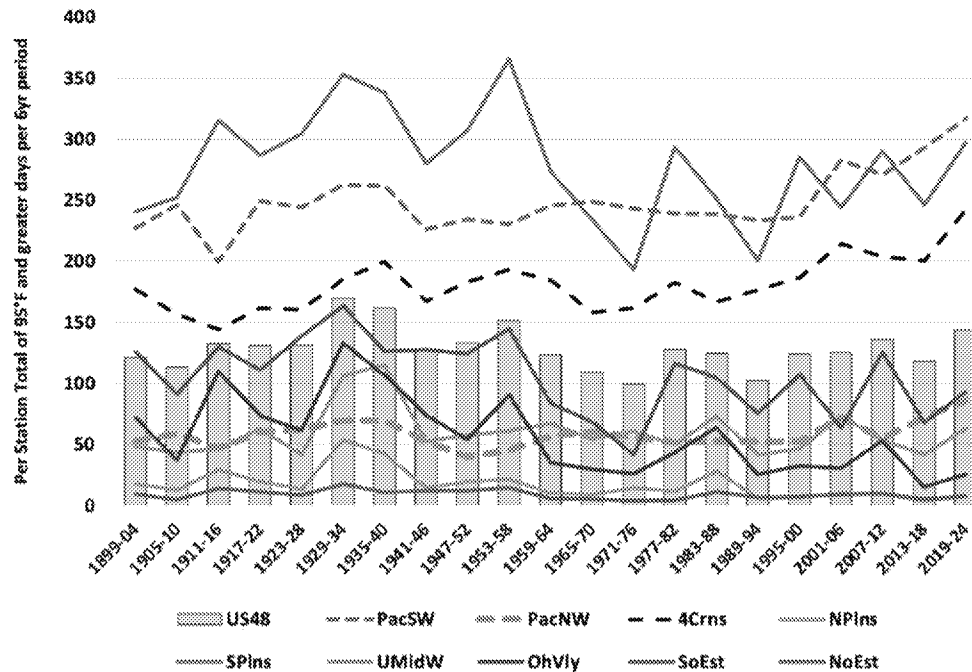


Figure 6.3.5. Total number of days $\geq 95^{\circ}\text{F}$ in 6-yr periods, U.S. 48 (bars) and regions (lines). A 6-year period is used as this evenly divides the 126-year record. US48: contiguous U.S. states. See Figure 6.3.2 for region names. Source: Author analysis of USHCN data.

In the past 126 years, the average CONUS station experienced 129 days exceeding 95°C per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, such threshold analyses must be interpreted with caution. Figure 6.3.5 shows that only three of the nine regions, all in the West, have experienced upward trends in the number of 95°F or hotter days (dashed lines). The CONUS as a whole has not, and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 referenced in the NCA5 quote will be examined more closely in Section 8.6.1. The evidence indicates that it was a single, unprecedented event in the record, not part of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was $+10.8^{\circ}\text{C}$, the most extreme Northern Hemisphere grid point summer anomaly in the 46 years from over 4 million grid values. In contrast, the global temperature anomaly during that time was virtually zero ($+0.03^{\circ}\text{C}$, Mass *et al.* 2024).

The NCA5 heading “The Risk of Temperature Extremes is Changing” suggests pervasive positive trends are now being observed in threshold temperatures, but that is not evident in the figures above.

6.3.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than a single daily record temperature. We measure “Heatwave Days” here as the count of all days in May-Sep each year that exceed the 90th percentile for that day and that lie within a period of at least six consecutive days. This is equivalent to the method used in NCA4, except that the reference period here is the entire record 1899-2024 while NCA4 truncated the reference period to 1961-1990, which was a cool interval. That truncation boosts positive results (days exceeding the 90th percentile) in years warmer than the reference period, especially starting in 1960 and moving to the present (see Figure 6.3.6 and discussion below).

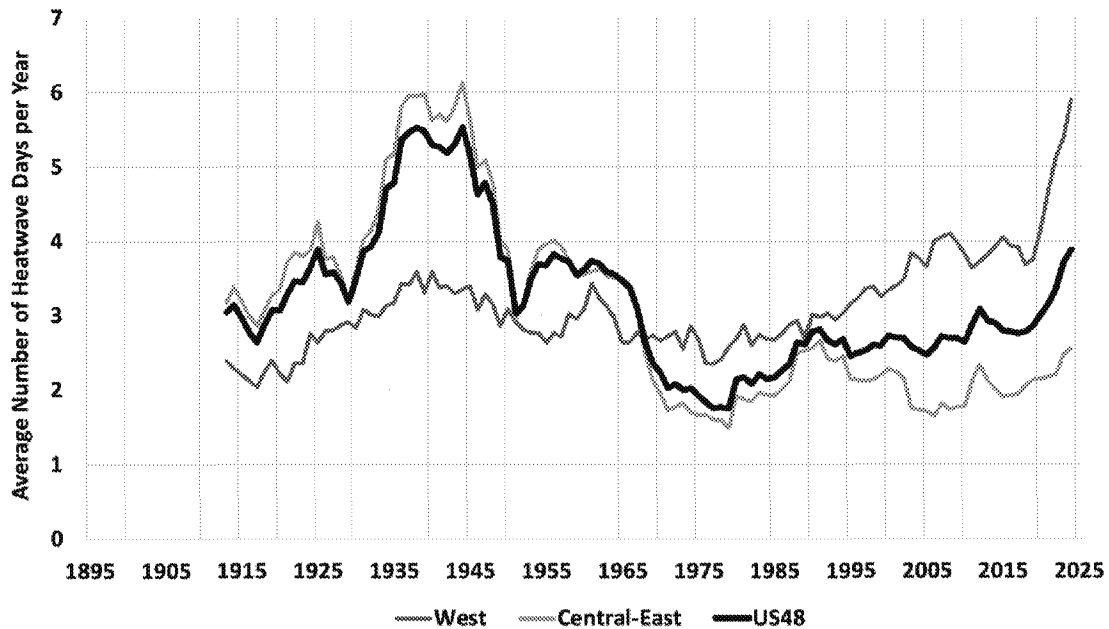


Figure 6.3.6 15-year trailing average of number of heatwave days per year per station in the CONUS (black line) and two regions: West (red), Central-east (green).

Figure 6.3.6 indicates that there are regional variations in heatwave activity. The excessive heat of the first half of the 20th century occurred primarily in the eastern two-thirds of the nation, while the West has seen a recent increase of heatwave days (NCA5). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20th century, but in the 21st century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago, consistent with the upper panel of our Figure 6.4.1 taken from NCA4.

This metric varies significantly with region. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

The analysis of heatwaves is an example of why it is important to consider complete datasets and appropriate metrics. The NCA5 directs readers to the website [[HYPERLINK "https://www.globalchange.gov/indicators/heat-waves"](https://www.globalchange.gov/indicators/heat-waves)] (USGCRP 2023) to view a figure showing the number of urban heatwaves by decade from the 1960s, which we reproduce as Figure 6.3.7.

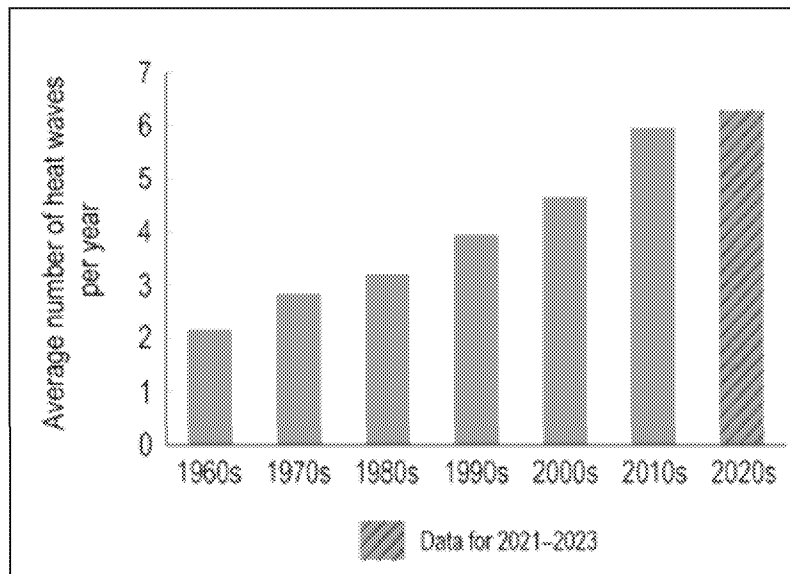


Figure 6.3.7: Average number of urban heatwaves per year for 50 large U.S. metropolitan areas, a misleading metric for reasons explained in the text. From [[HYPERLINK "https://www.globalchange.gov/indicators/heat-waves"](https://www.globalchange.gov/indicators/heat-waves)] (accessed May 22, 2025).

The figure shows a monotonic increase in each decade from two occurrences per year in the 1960s to six in the 2020s. The definition of a heatwave used is an unusual but practical measure of human discomfort - a period of at least 2 consecutive days when the *minimum* apparent temperature (combination of temperature and humidity) exceeds the 85th percentile. Note too, the dataset is limited to the 50 largest U.S. cities.

Given the unusual heatwave definition and urban focus, these increasing values since 1960 presented in USGCRP (2023) are not informative about long term trends or the influence of GHG emissions for at least two reasons. First, as shown in Figures 6.3.1 and 6.3.6, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. Second, post-1960 urbanization in these cities is a major factor in the rise of T_{min} relative to co-located T_{max} and relative to T_{min} at nearby rural stations. This does not dismiss the real rise in nighttime temperatures in major U. S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons that summer T_{max} (especially in rural areas) is a better metric for detecting changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy *et al.* 2009). For CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves against the background of urbanization and natural climate variability.

6.4 Extreme precipitation

AR6 assessed that an increase in heavy precipitation has been observed in data starting in the 1950s.

AR6: The frequency and intensity of **heavy precipitation events have increased** since the 1950s over most land area for which observational data are sufficient for trend analysis (high confidence). (SPM A3.2)

AR6: In North America, there is robust evidence that the **magnitude and intensity of extreme precipitation has *very likely* increased** since the 1950s. Both [one-day maxima] and [5-day maxima] have significantly increased in North America during 1950-2018. (Chapter 11, p. 1560)

The U.S. National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of CONUS, especially the Northeast, when starting the analysis in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme precipitation events are in the Northeast and the smallest in the West, a pattern counter to the changes in temperature extremes (Figure 6.3.6).

McKittrick and Christy (2019) examined long-term and consistent station observations of extreme daily precipitation to test some of these NCA claims for the Southeast and West Coast using a trend model with a non-parametric variance estimator robust to the complex autocorrelation properties of precipitation data. When the time series were extended back in time (as far as 1872 in some cases) or started later (1978), there were no significant trends for either region.

These findings have been updated for this report (McKittrick and Christy 2025) with similarly constructed observations from 29 stations on the CONUS Pacific Coast (1893ff from San Diego CA to Blaine WA) and 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC), also adding 27 stations in the Northeast (1888ff from Buffalo NY to Eastport ME). The locations are shown in Figure 6.4.1. The stations were selected based on availability of long-term high-quality records. The regions are each associated with important features of extreme precipitation behavior: the Pacific coast is associated with landfalling atmospheric rivers for which AR6 cites evidence of increasing activity since 1948 with further increases expected as the world warms (AR6 8.3.2.8.2); the NCA report indicates that the Northeast has experienced the greatest increase in extreme events, and the Southeast is also a place noted in the NCAs as having increased extreme events.

The results of applying the analysis of McKittrick and Christy (2019) were as follows for each region, then followed by further explanation.

Pacific Coast heavy rainfall events

- The average precipitation trend is statistically significant (downwards) in Astoria OR; insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Big Sur CA; insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Aberdeen WA and Big Sur CA and negative and significant in Newport OR (insignificant elsewhere).
- Averaged over all stations in the region, none of these three trend parameters is statistically significant.

The Pacific Coast receives considerable precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov *et al.* 2017, Pan *et al.* 2024). The worst series of such events in recent history was the so-called ARkStorm that occurred during December 1861 and January 1862; it dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Null and Hulbert 2007). Additionally, Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1800 years, occurring at intervals of 300 years or so (Porter *et al.* 2011).



Figure 6.4.1: Locations of precipitation monitoring stations used in this report. Orange: Pacific coast. Blue: Northeast. Green: Southeast. Data from McKittrick and Christy (2025).

We examine occurrences of 5-day deluges as follows. Taking the Pacific coast as an example, a 130-year span contains 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values across the sample. A single year might have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5yr events. If there are no trends in precipitation, then the total number of these events across all stations should be evenly spread over the years. In Fig. 6.4.2 we show the distribution in time of these events for the Pacific coast. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of such precipitation metrics, there is no indication of a tendency to become more frequent over time.

Southeast heavy rainfall events

- The trend in average precipitation is positive and statistically significant in Mobile AL and Quitman GA but insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Mobile AL but insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Vicksburg MS and Norfolk VA but insignificant elsewhere.
- Averaged over all stations in the region none of these three trend parameters is statistically significant

Figure 6.4.3 is analogous to Figure 6.4.2 for the last 150 years in the Southeast humid zone. The temporal pattern of 5-day totals of the 1-in-5yr heavy events is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 -- an increasing frequency of heavy events due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.

BOX: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 7.2.

Event	Record (inches)	Year
3-day	6.94	2023
5-day	8.55	2023
14-day	12.62	2023
30-day	18.93	1998

Table 6.2: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent years. 2023 appears to be an exceptional year and since it is near the end of the sample, it might suggest that the climate has shifted into a more hazardous state, perhaps because of human influences. [Note “2023” indicates the event occurred in the water-year of Aug 2022 to Jul 2023.]

But the picture is very different if we use a sample that begins 45 years earlier, in 1850. Table 6.3 shows that the record-setting events all happened in the 1860s. Furthermore 2023 is now not even in 2nd place but falls to 3rd or 4th place. And comparing the records of the two charts shows the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

Event	Record (inches)	Year	Rank of 130-yr extreme listed in Table 6.2
3-day	8.85	1867	3
5-day	9.80	1867	3
14-day	19.05	1862	4
30-day	28.25	1862	2

Table 6.3: Extreme rainfall records, San Francisco, 1850-2024.

The range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter *et al.* (2011) discovered that in the past 1,800 years at least six megastorms were more intense than the devastating 1861-62 ARkStorm that struck the region. Evidently such extreme events, “unprecedented” in our 1895-2024 sample, have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (Section 8.6). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50 percent determined when adding only 45 more years of observations. Compared to millennia-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own, even without human influences.

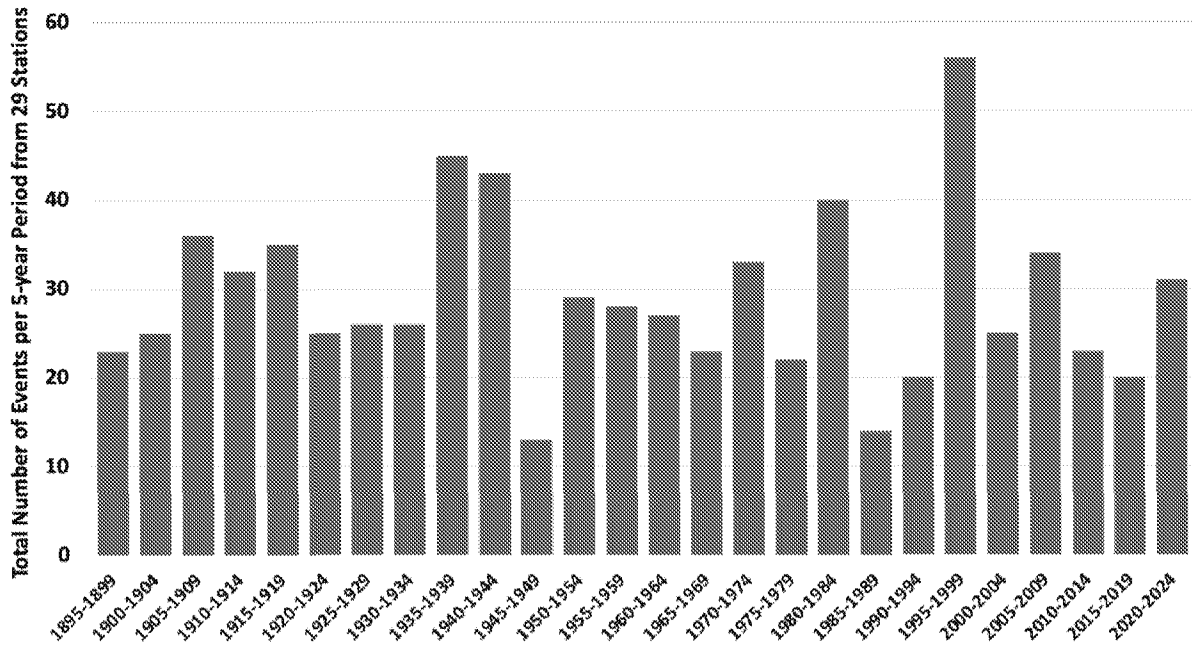


Figure 6.4.2. The time distribution by 5-year periods of the 26 heaviest (1-in-5 yr) occurrences for 29 stations on the Pacific coast.

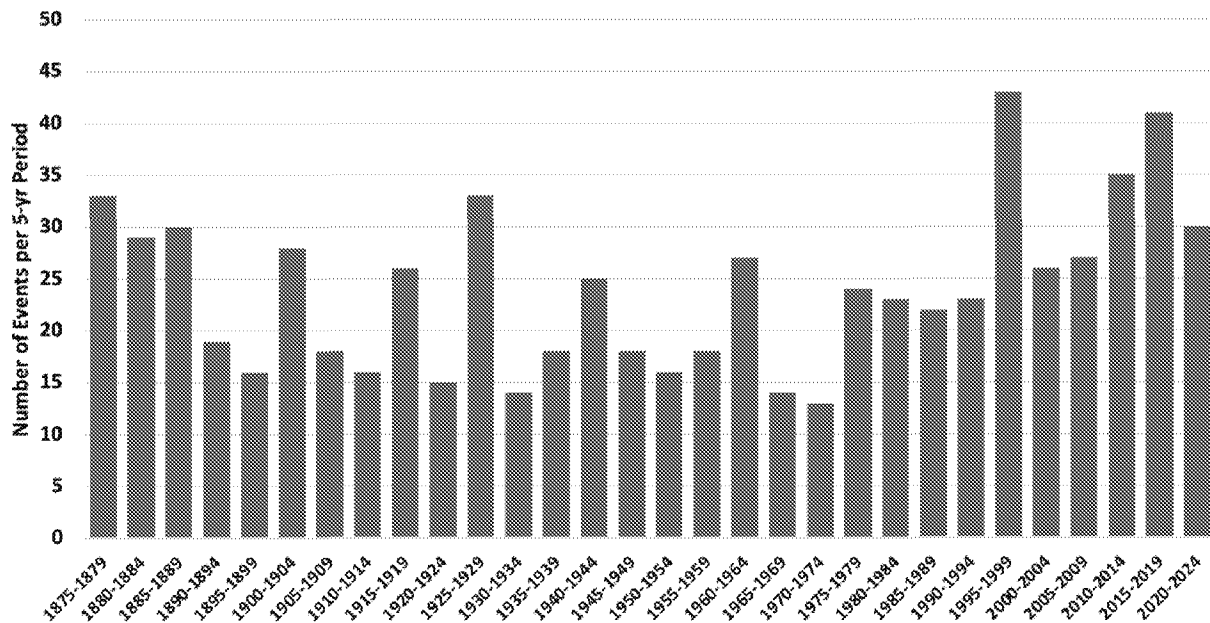


Figure 6.4.3. As in Fig. 6.4.2 but for the heaviest 30 (1-in-5yr) events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

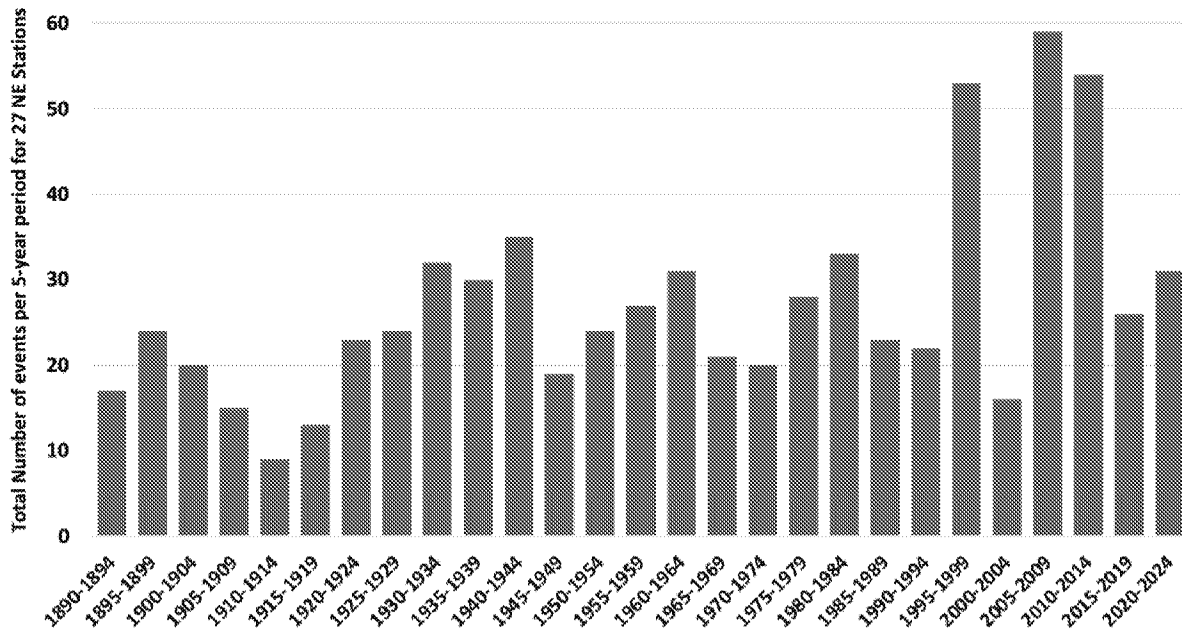


Figure 6.4.4. As in Fig. 6.4.2 but for the heaviest 27 (1-in-5yr) 3-day precipitation events for 27 Northeast stations from NY to ME, including Montreal.

Northeast heavy rainfall events

- The trend in average precipitation is positive and statistically significant in 12 of 27 locations and also in the regional average.
- The trend in rainfall variance is positive and significant in Portland ME, Albany NY, Buffalo NY and Eastport ME but insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Portland ME, Gardiner ME and Eastport ME but insignificant elsewhere.
- When averaged over all stations in the region, there is no statistically significant trend in either the precipitation variance or maximum

Fig. 6.4.4 is analogous to Figure 6.4.2 for the last 135 years in 27 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest temporal variations in time. In this region, 77 percent of events occur during June to October and are dominated by incursions of hurricanes, tropical storms, or tropical storms that transition to extratropical systems. According to NCA4 and NCA5 this region experienced the largest increases in extreme events, so it merits a closer examination.

There is a noticeable clustering of extreme events from 1995 to 2014. Howarth *et al.* (2019) examined a similar region as in Fig. 6.4.4 that includes PA and NJ and reported significant differences in various precipitation extremes between two 18-year periods, 1979-96 and 1997-2014. That included a 317 percent increase in 24-hr events exceeding 6 inches, while we find a 58 percent increase over the same years. However, Figure 6.4.4 shows that frequency drops sharply after 2014, returning to the long-term average in the subsequent 5-year intervals, again illustrating the perils of drawing conclusions from short-term trends in highly variable metrics.

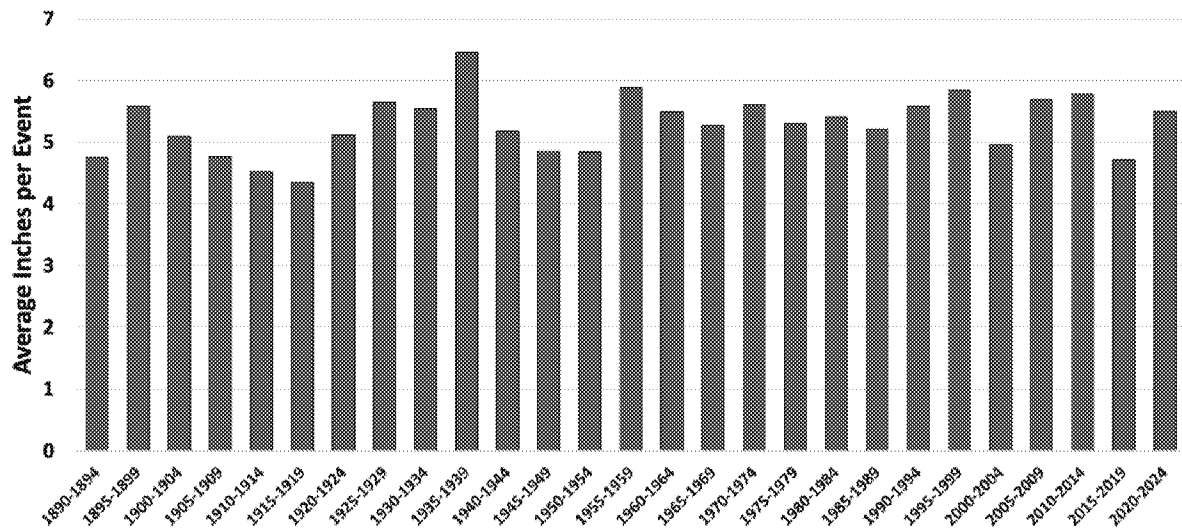


Figure 6.4.5. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

The high percentage increase in the Howarth *et al.* sample is associated with small numbers at relatively few locations: there were only 6 in the first period and 25 in the second across 58 stations. Most of the stations did not record such an event. If there is a region-wide increase in heavy events, it should be seen in the average across all stations. Figure 6.4.5 shows the average precipitation in the 1-in-5 yr events across the NE. The trend is only +0.04 inches/decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 6.4.4 and 6.4.5 thus suggest that though there was a surge in the number of events at a few locations during the 1995 to 2014 interval, there was no regional pattern and the change did not persist beyond 2014.

Jong *et al.* (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded “The autumn extreme precipitation trend over the Northeast U.S. is primarily attributed to tropical cyclone-related events since the 1990s.” The question then becomes: “Was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs?” Jong *et al.* examined CMIP-6 model output which suggests that there will be fewer such systems in the 21st century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 6.4.5 where the amount-per-event has remained steady over the 135-year period.

There is some evidence to indicate the heaviest rainfall events might be redistributed due to the impact of urban infrastructure on the local weather (e.g., Pielke Sr. *et al.* 2011, Zhang *et al.* 2018, Yang *et al.* 2024). Yang *et al.* state “Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with dispersed development.” While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 6.4.5.

In summary, some U.S. regions show short-duration increases in extreme precipitation events, consistent with natural variability. But analysis of long term, nationwide historical records that considers the autocorrelation properties of precipitation data does not support the claim that extreme short-duration rainfall events are becoming more frequent or intense.

6.5 Tornadoes

AR6 assesses tornado trends in the U.S. as follows:

[O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

The monitoring of weak tornadoes has changed over time. The growth of rural populations and the increasing ability to take video with hand-held devices has led to more frequent reports of weak tornadoes that produce minimal damage. In contrast, strong to violent tornadoes have been observed more consistently over time. Note that tornado strength is measured by the damage it produces, not by the visual appearance of the funnel. Limited real-time observational capabilities in earlier decades did not prevent identification because strong to violent tornadoes leave much more damage which will be assessed later even if the tornado itself was not observed. Since statistics began in 1950, there has been a substantial decrease (by about 50%) in the number of strong to violent tornadoes as shown in Fig. 6.5.1a.

To summarize, there is a noticeable downward trend in the number of severe tornadoes in the U.S. since 1950. After 1990 the number of weak tornadoes in the U.S. has remained roughly constant; data before that are incomplete due to limited monitoring.

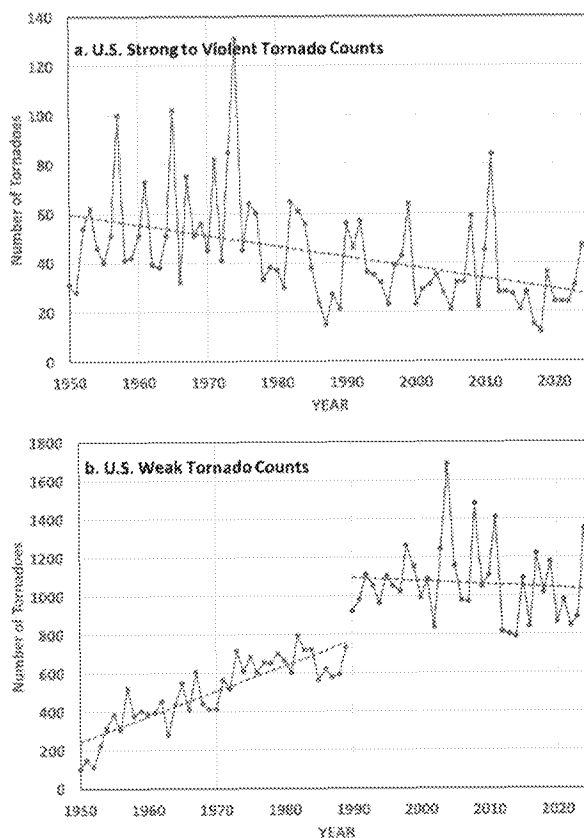


Figure 6.5.1. Annual U.S. tornado counts for (a) strong to violent tornadoes (EF3 to EF5), and (b) weak tornadoes (EF0 to EF2). Based upon NOAA Storms

Prediction Center data, available at https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv

6.6 Flooding

Changes in floods were assessed as follows:

AR6: The SREX **assessed low confidence for observed changes in the magnitude or frequency of floods** at the global scale. This assessment was confirmed by the AR5 report. The SR15 found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. . . [H]ydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales. (Chapter 11.5)

AR6: [T]he seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). Confidence about peak flow trends over past decades on the global scale is *low*. (Chapter 11.5)

NCA4: Trends in extreme high values of streamflow are **mixed** across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude **but does not provide robust evidence** that these trends are attributable to human influences (pp. 240-241)

The absence of detectable US-wide trends in flooding is consistent with the findings in Section 6.4 of absence of coherent changes in extreme precipitation.

6.7 Droughts

Assessments of drought trends were as follows.

AR6: Few AR6 regions show observed increases in meteorological drought (Section 11.9, p. 1575),

AR6: Increasing trends in agricultural and ecological droughts have been observed on all continents (*medium confidence*), but decreases only in one AR6 region (*medium confidence*). Increasing trends in hydrological droughts have been observed in a few AR6 regions. (Chapter 11 Summary)

NCA4: As a consequence of this increased precipitation, **drought statistics over the entire CONUS have declined**. (p. 233)

NCA4: Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the **1930s remains the benchmark** drought and extreme heat event in the historical record (very high confidence). (p.231)

SREX: From a paleoclimate perspective, **recent droughts are not unprecedented**, with severe ‘megadroughts’ reported in the paleoclimatic record for Europe, North America, and Australia. (p. 170)

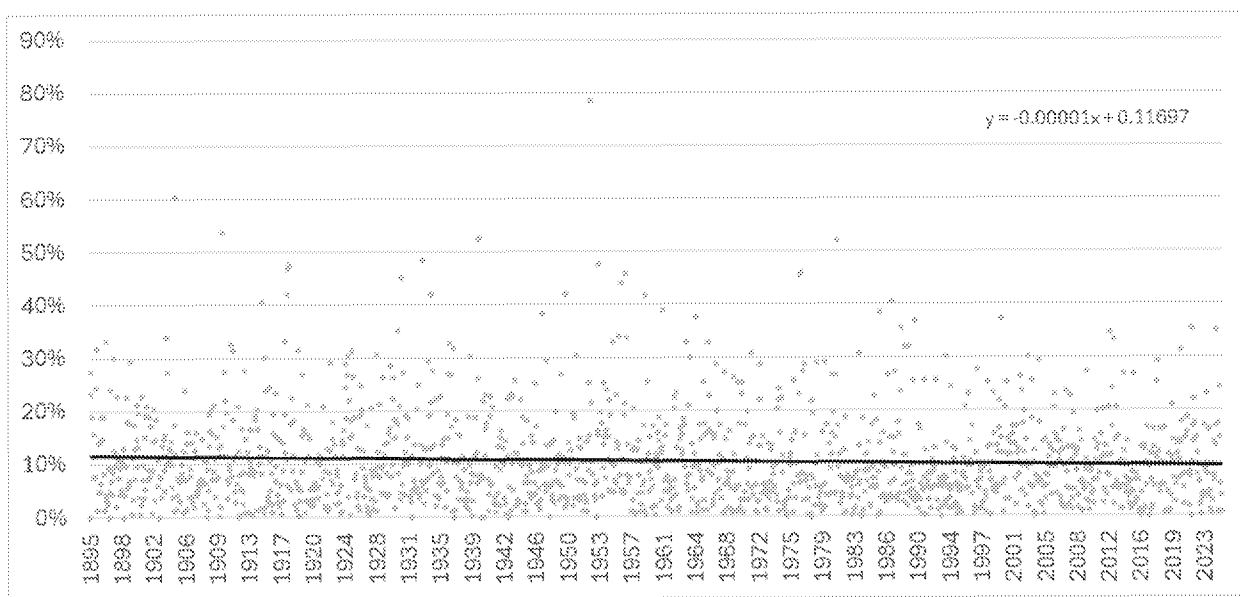


Figure 6.7.1: Monthly percent of US classified as “Very Dry” 1895—2025. Data source: NOAA [[HYPERLINK "https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0"](https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0)] least squares trendline added.

As shown in Figure 6.7.1, U.S. long-term data shows an insignificantly declining trend in extreme dryness (-0.001 percent per year)

Kogan *et al.* (2020) examines a 38-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: “it is possible to state firmly that global and main grain countries’ drought area and intensity trends have not been following global climate warming since 1980’s.”

In summary there is no evidence of increasing drought frequency or intensity in the U.S. or globally over recent decades.

6.8 Wildfires

The IPCC has not provided an assessment of wildfires. As shown in Figure 6.8.1, global wildfire activity as measured by European Space Agency shows a downward trend in the 21st century.

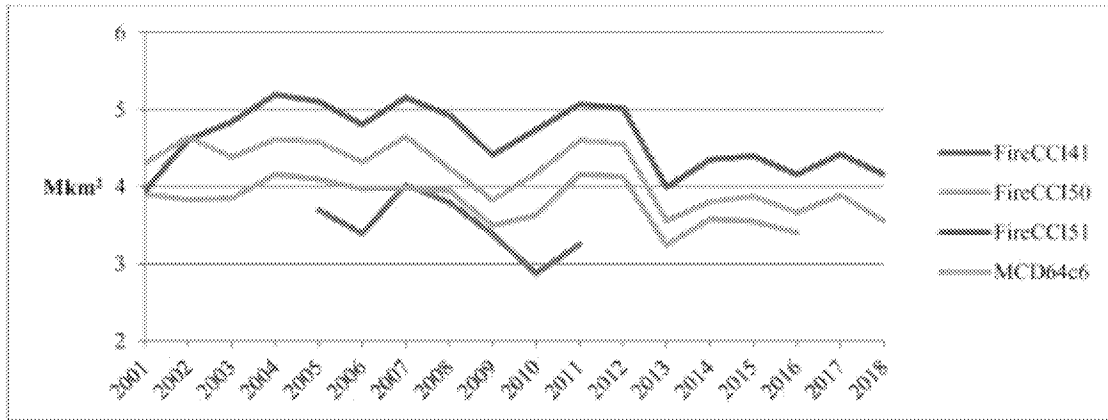


Figure 6.8.1: Global wildfire area 2001-2018. Source: From Lizundia-Loiola *et al.* (2021) Figure 12. The different coloured lines represent data products derived from different satellites and algorithms

Global data show that wildfire coverage is constant or declining on every continent (Samborska and Ritchie, 2024).

Active fire suppression since 1900 makes it difficult to establish a natural baseline for wildfire activity in the U.S. Paleoclimatic evidence indicates that past activity was much higher than today. Marlon *et al.* (2012) used sedimentary charcoal layers to reconstruct fire history of western U.S. for the past 1400 years and also fit a model to predict fire activity as a function of climatic conditions. Their results are summarized in Figure 6.8.2 below (from Figure 2 in their paper). There has been a growing wildfire deficit over the 20th century. In other words, however much fire was observed in the 20th century, it was less than what would have been observed in previous centuries based on the climatic conditions. Parks *et al.* (2025) likewise find that despite the recent increase in wildfire burn area in North America, a significant wildfire deficit remains relative to historical wildfire regimes.

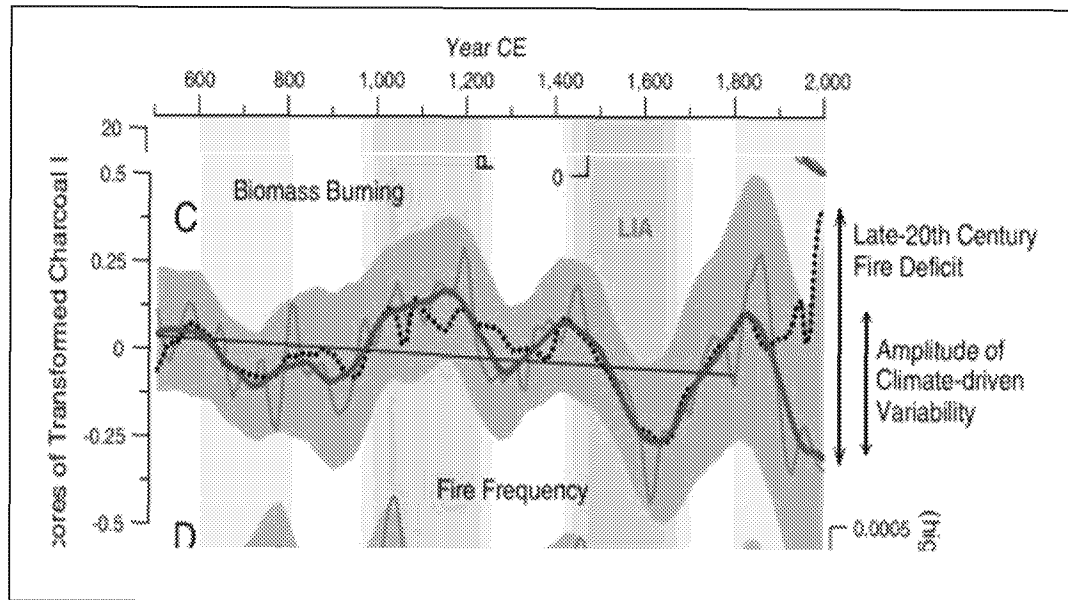


Figure 6.8.2 Fire frequency and fire deficit in the US. The red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based climatic conditions. Source: Marlon *et al.* (2012) Figure 2.

U.S. data from the National Interagency Fire Centre (NIFC) from 1926 to 2023 are shown in Figure 6.8.3. The NIFC has removed the pre-1960 data from its current website on the grounds that measurement methods changed after 1960 making the comparison unreliable. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

Forest fires have always been a part of nature, and they can certainly create conditions that are inhospitable in the short term for all life, including humans. Science has confirmed the overall benefit and necessity of forest fires. While recent high-profile fires and seasons serve as a reminder of the potential destructive impact, the highest profile U.S. forest fire remains the 1910 Big Blowup fire in the U.S. west, which destroyed over three million acres and eliminated entire towns like Taft, MT (Apple, 2020). The 1910 fire reshaped the U.S. Forest Service (National Forest Foundation 2022) leading to a focus on fire suppression with a primary goal of defeating all forest fires (Forest History Society, 2022). This led to the “10 am rule” in 1935 requiring that all fires spotted on any day had to be controlled by 10 am the following day (National Forest Foundation, 2022).

While defeating all fires seemed a noble goal, questions began to arise as to whether this behavior “followed the science” (U.S. Forest Service, 2022). Over time the U.S. Forest Service has begun to rethink its goals, recognizing that new approaches such as prescribed burns, fuel elimination, and controlled wildfires are more appropriate (Sommer, 2016). Recent research is validating this approach and recognizing that more frequent smaller fires likely result in healthier forests, water ecosystems and biodiversity (Stephens *et al.*, 2021).

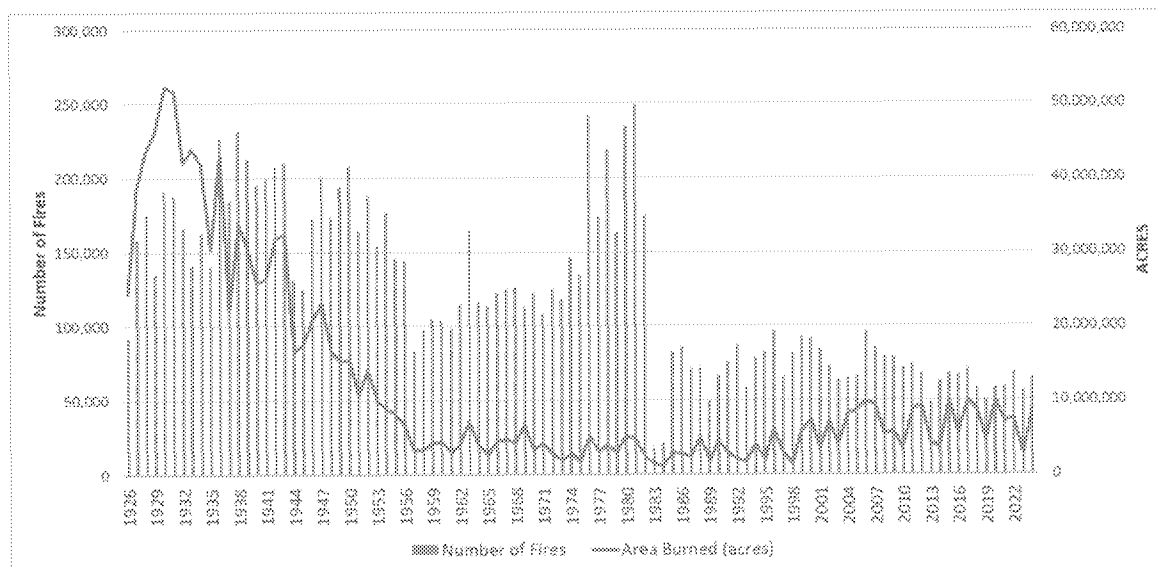


Figure 6.8.3: U.S. wildfires 1926 to 2023. Source: Post-2018: National InterAgency Fire Center data [[HYPERLINK "https://www.nifc.gov/fire-information/statistics/wildfires"](https://www.nifc.gov/fire-information/statistics/wildfires)]. Pre-2017 webarchive.org (n.d.).

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7 CHANGES IN SEA LEVEL

Chapter Summary

Since 1900, global average sea level has risen by about 8 inches. Sea level change along U.S. coasts is highly variable, associated with local variations in processes that contribute to sinking and also with ocean circulation patterns. The largest sea level increases along U.S. coasts are Galveston, New Orleans, and the Chesapeake Bay regions - each of these locations is associated with substantial local land sinking (subsidence) unrelated to climate change.

Extreme projections of global sea level rise are associated with an implausible extreme emissions scenario and inclusion of poorly understood processes associated with hypothetical ice sheet instabilities. In evaluating the IPCC AR6 projections to 2050 (with reference to the baseline period 1995-2014), almost half of the interval has elapsed by 2025, with sea level rising at a lower rate than predicted. U.S. tide gauge measurements reveal no obvious acceleration beyond the historical average rate of sea level rise.

7.1 Global sea level rise

Global sea level rise is arguably the most important climate impact driver that is unambiguously associated with increasing temperatures. At the global level, warming raises sea level through thermal expansion of sea water and through melting of glaciers and ice sheets. Variations in land water storage are another important factor. At the regional scale, sea level change is influenced by large-scale ocean circulation patterns, and geologic processes and deformation from the redistribution of ice and water. Locally, vertical land motion from geologic processes, ground water withdrawal, and fossil fuel extraction are also important.

The IPCC AR6 estimates that global mean sea level increased by 7.9 (5.9–9.8) inches between 1901 and 2018, with the rate of sea level rise accelerating in recent decades. At the ocean basin scale, sea levels have risen fastest in the Western Pacific and slowest in the Eastern Pacific over the period 1993–2018 (Fox-Kemper *et al.*, 2021). The rate of global sea level rise is estimated to be 0.12 inches/year, about the height of two stacked pennies (NASA, 2020).

The observing systems for global sea level rise have advanced significantly in the satellite era, particularly with the advent of satellite altimeters in 1993. Local tide gauges have provided useful data for the past century, and even longer for a few locations. Following the end of the Little Ice Age in the mid-nineteenth century, tide gauges show that the global mean sea level began rising during the period 1820–1860, well before most anthropogenic greenhouse gas emissions.

7.2 U.S. sea level rise

Observed and predicted rates of mean global sea level rise might have little scientific relevance for specific locations, owing to local processes (NOAA, 2025). Figure 7.1 shows that in Canada and Alaska (and also northern Washington), sea level is decreasing, owing to uplift from glacial rebound. Most of the Pacific coast tide gauges show low rates of sea level rise, while largest U.S. rates are on the Gulf coast (Louisiana and Texas) and in the mid-Atlantic states (Chesapeake Bay region).

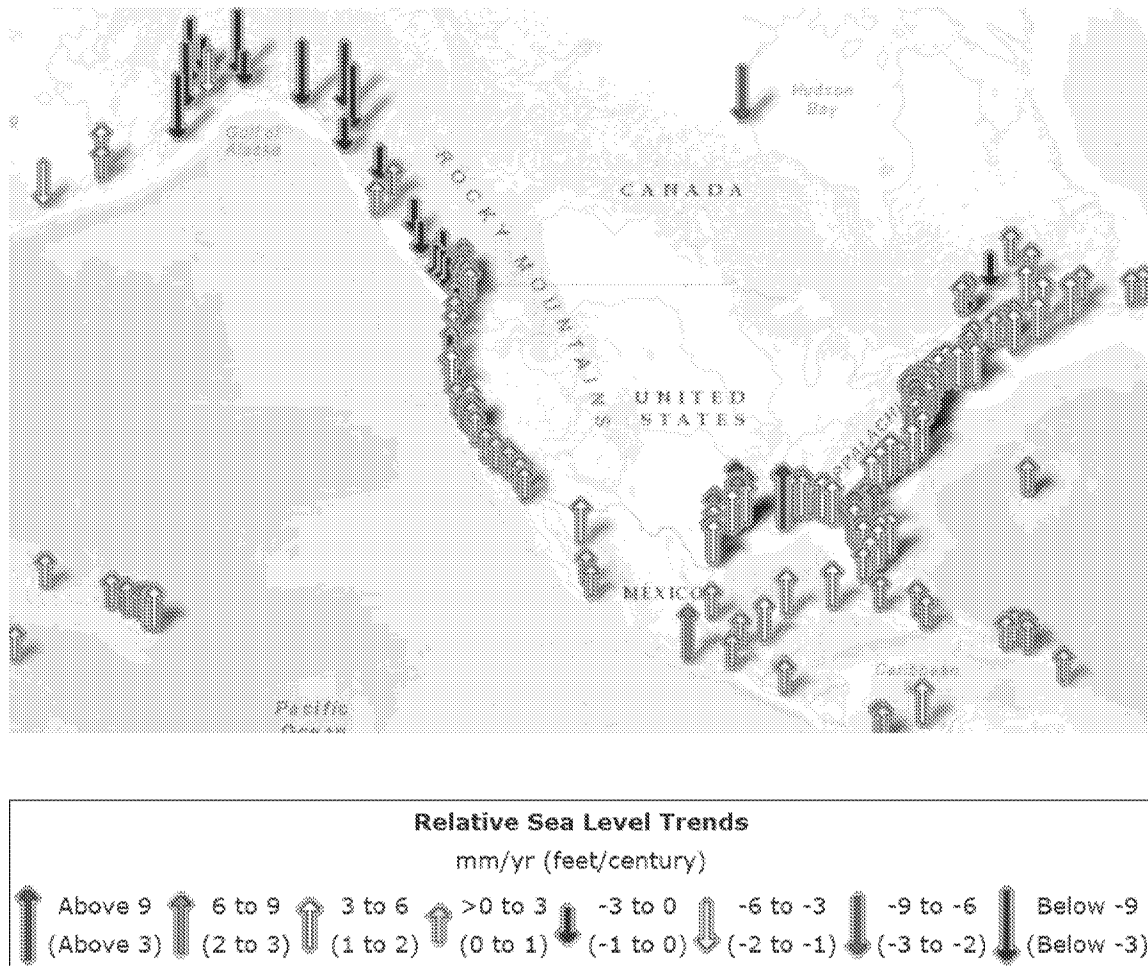


Figure 7.1. Map of rates of relative sea level rise along the U.S. coast (NOAA, <https://tidesandcurrents.noaa.gov/sltrends/>). For reference, 3 mm = 0.12 in.

Measurements of relative sea level rise from tide gauges conflate the climatologically relevant increase in the volume of seawater with local vertical land motion. The latter, which varies from place to place, is best measured using a Global Positioning System (GPS) station located near the tide gauge. It is driven by a range of processes that can be comparable to the climate signal and can locally exacerbate (subsidence/sinking) or mitigate (uplift) the risk of sea level rise (Wöppelmann and Marcos, 2016). Human activities triggering subsidence are often significant. They include soil drainage (*e.g.* for urban development) and subsurface extraction of groundwater or hydrocarbons.

Table 7.1 shows absolute sea-level rise (ASLR) for selected locations, determined from the sum of uncorrected sea-level rise as estimated from tide gauge time series (RSLR) (NOAA, 2025) and the vertical land motion (VLM) measurements (NAS, 2012; Letetrel *et al.*, 2015; Karegar *et al.*, 2016). The absolute sea level rise for each of these locations is significantly smaller than the measured relative sea level rise owing to local subsidence. More than half of the measured relative sea level rise is attributed to land sinking for these locations: San Francisco, Galveston, Grand Isle. For reference, the global average rate of absolute sea level rise is estimated to be 0.12 inches/year.

Location	RSLR	VLM	ASLR
San Francisco, CA	+0.08	-0.06	+0.02
Galveston, TX	+0.26	-0.19	+0.07
Grand Isle, LA	+0.36	-0.28	+0.08
St Petersburg, FL	+0.12	-0.02	+0.10
New York City, NY	+0.11	-0.05	+0.06

Table 7.1 Absolute sea level rise (inches/year) consisting of Relative Sea Level Rise (RSLR) plus Vertical Land Motion (VLM)

San Francisco Bay

Over the past 100 years, relative sea level in the San Francisco Bay area has risen by 7.8 inches, at an average rate of 0.08 inches/year (Figure 7.2). As shown in Table 7.1, San Francisco’s vertical land motion is -0.06 inches/year (sinking), producing a recent absolute rate of +0.02 inches/year. Portions of Treasure Island, San Francisco International Airport, and Foster City are sinking as fast as 0.4 inches/year (Shirzaei and Bürgmann, 2018). Problems in the San Francisco Bay area, including threats to the airport, are caused primarily by soil compaction in landfill zones that were formerly wetlands, not by the slow creep of global sea level rise.

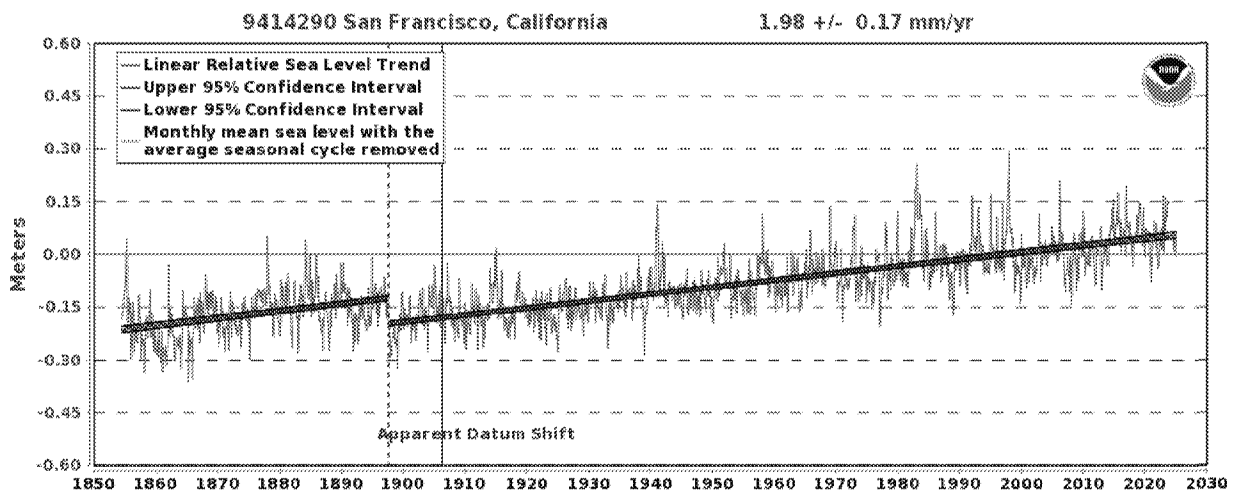


Figure 7.2. Tide gauge measurements at San Francisco, California, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290 (downloaded 4/22/25).

Galveston - Houston

Long-term tide measurements at Galveston Pier 21 show sea level rise of 2.18 feet in the past century, or a rate of 0.26 inches/year (Figure 7.3). Vertical land motion (subsidence) at Galveston is estimated at -0.19 inches/year, yielding an absolute rate of rise of +0.07 inches/year (Table 7.1). The U.S. Geologic Survey found that most of the land-surface subsidence in the Houston-Galveston region is a direct result of groundwater withdrawals (Kasmarek and Ramage 2017), which caused compaction of the aquifer sediments, mostly in the fine-grained silt and clay layers. By 1979, as much as 10 feet of subsidence had occurred in Houston.

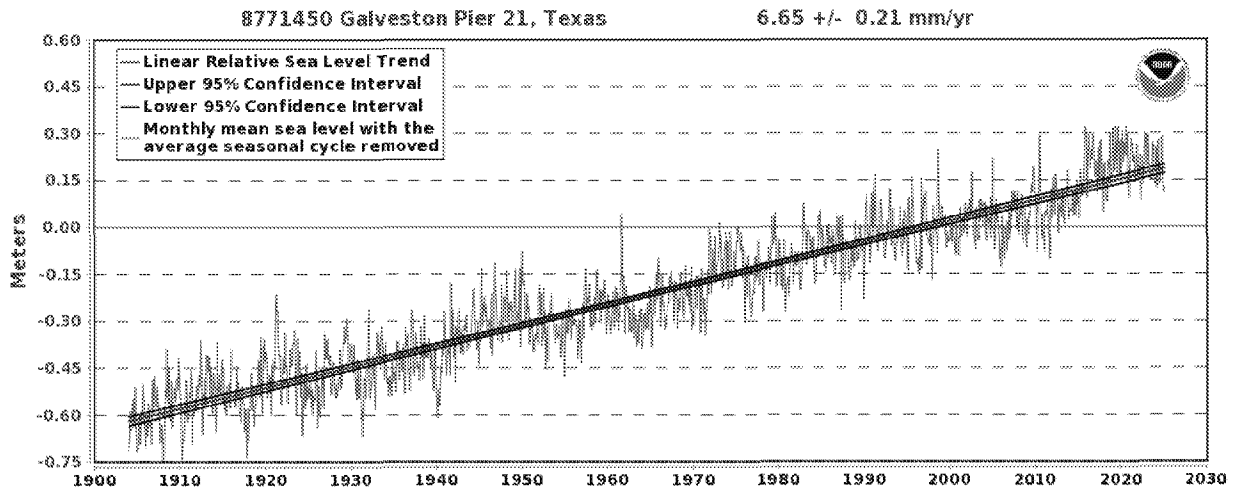


Figure 7.3. Tide gauge measurements Galveston Pier, TX, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8771450 (downloaded 4/22/2025).

New Orleans and the Mississippi delta

Long-term tide gauge measurements at Grand Isle, Louisiana, show that sea level has risen by slightly more than 3 feet over the last 100 years at an average rate of 0.36 inches/year (Figure 7.4). Vertical land motion (subsidence) is estimated -0.28 inches/year. Table 7.1 gives the absolute sea level rise as +0.08 inches/year.

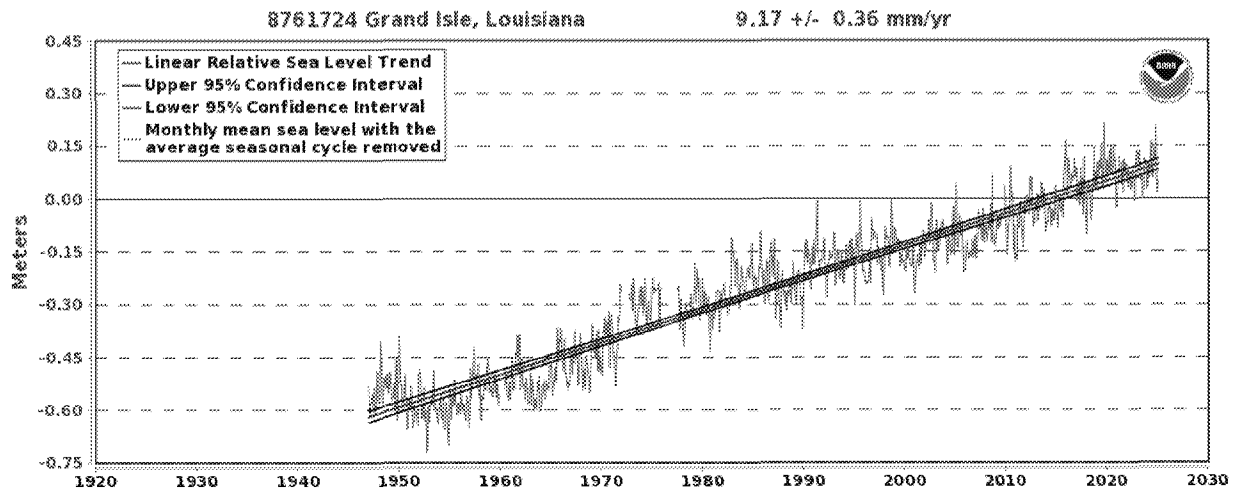


Figure 7.4. Tide gauge measurements at Grand Isle, LA, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8761724 (downloaded 4/22/25).

The issues of sea level rise and land loss in the Mississippi Delta region are complex, with geological subsidence and the decline in sediment transported by the Mississippi River being the dominant drivers. The construction of dams in the basin since the 1950s has decreased the Mississippi’s suspended sediment load by ~50 percent (Maloney 2018). A new subsidence map of coastal Louisiana finds the coastal region to be sinking at about one third of an inch per year (Neinhuis *et al.* 2017), associated with groundwater and resource withdrawal. As the city’s elevation averages one to two feet *below* sea level, sea level rise from anthropogenic warming is hardly the dominant driver of New Orleans’ problems.

New York City

New York City is particularly vulnerable to the effects of sea level rise because it is built primarily on islands and has 520 miles of coastline. Measurements by a tide gauge at the southern tip of Manhattan (The Battery) show that relative sea level has risen over 11 inches over the past century, at an average rate of 0.11 inches/year (Figure 7.5). But vertical land motion in the New York City area is -0.05 inches/year (roughly 5 inches per century), so that the absolute rate of sea level rise at The Battery is 0.06 inches/year, or about 55 percent of the measured relative sea level rise.

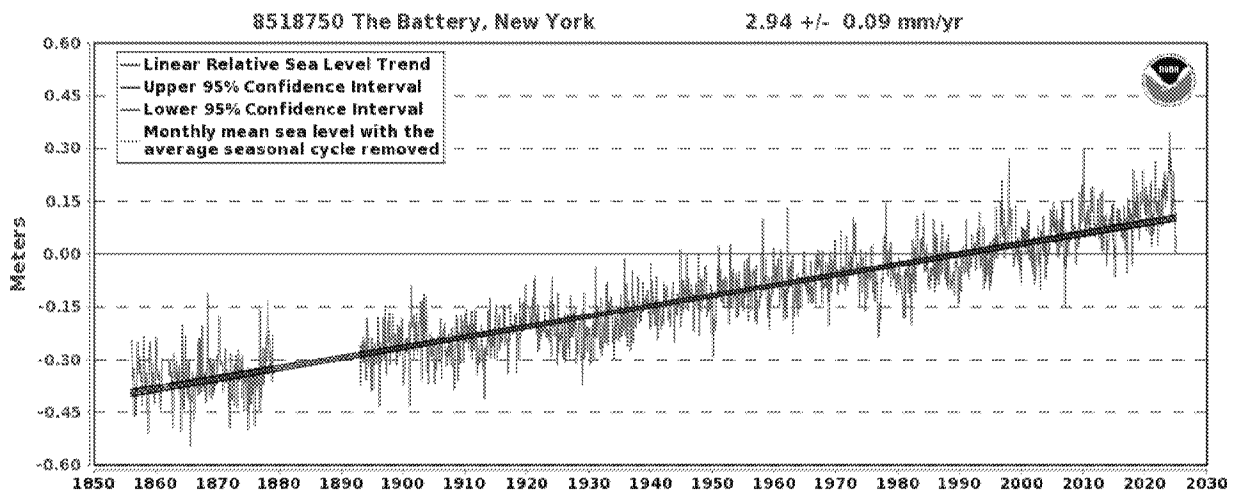


Figure 7.5. Tide gauge measurements at The Battery, New York, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750 (downloaded 4/22/25).

7.3 Projected sea level rise

The concern over sea level rise is not about the roughly eight inches of global rise since 1900. Rather, it is about projections of *accelerated* rise based upon simulations of a warming climate through the 21st century.

AR6 finds *high agreement* across published global mean sea level projections for 2050 with little sensitivity to emissions scenarios. Considering only projections incorporating ice-sheet processes in whose quantification there is at least *medium confidence*, the global sea level projections for 2050, across all emissions scenarios, fall between 3.94 and 15.75 inches (5th–95th percentile *very likely* range) relative to the 1995–2014 baseline period (Fox-Kemper *et al.*, 2021).

Conversely, AR6 states there is *low agreement* across published global mean sea level projections for 2100, particularly for higher emissions scenarios. Considering only projections representing ice sheet processes in whose quantification there is at least *medium confidence*, the AR6 global mean sea level projections for 2100 lie between 7.87 and 39.37 inches (5th–95th percentile *very likely* range) under the medium emissions scenario SSP2–4.5 (Fox-Kemper *et al.*, 2021). There is deep uncertainty surrounding projections of sea level rise to 2100 owing to uncertainties in ice sheet instabilities, particularly for the higher emissions scenarios.

In February 2022, NOAA issued its projections of sea level rise for various sites along the U.S. coast (Sweet *et al.*, 2022). They claim that by 2050, the sea will have risen one foot at The Battery in Manhattan (relative to 2020). A one-foot rise in thirty years would be more than twice the current rate and about three times the average rate over the past century. In that historical context, NOAA’s projection is remarkable—as shown in Figure 7.6, it would require a dramatic acceleration beyond anything observed since the early 20th century. But even more noteworthy is that Sweet *et al.* (2022) say this rise is “locked in”—it will happen no matter what future emissions are. We should know in a decade or so whether that prediction has legs.

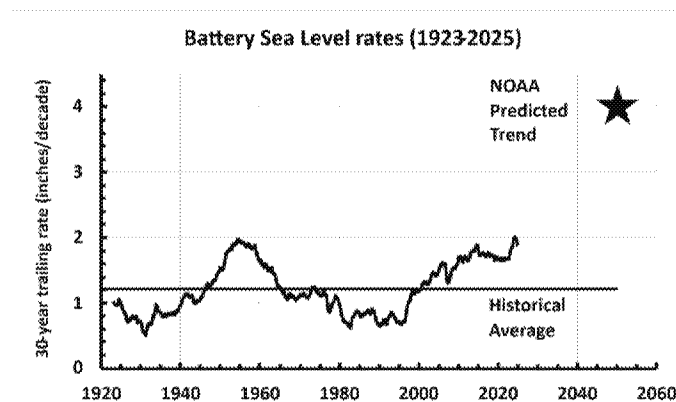


Figure 7.6 Rate of sea level rise at the Battery in Manhattan. Shown is the historical thirty-year trailing trend, together with the allegedly “locked in” NOAA predicted trend for 2050. Historical data: NOAA Tides and Current.

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8 UNCERTAINTIES IN CLIMATE CHANGE ATTRIBUTION

Chapter summary

“Attribution” refers to identifying the cause of some aspect of climate change, specifically with reference to anthropogenic activity. There is an ongoing scientific debate around attribution methods, particularly regarding extreme weather events. Attribution is made difficult by high natural variability, the relatively small expected anthropogenic signal, lack of high-quality data, and reliance on deficient climate models. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.

Substantive criticism of the main IPCC assessments of the role of CO₂ in recent warming focus on inadequate assessment of natural climate variability, uncertainties in measurement of solar variability and in aerosol forcing, and problems in the statistical methods used for attribution.

The IPCC does not make attribution claims for most climate impact drivers related to extreme events. Statements related to statistics of global extremes (*e.g.* event probability or return times, magnitude and frequency) are not generally considered accurate owing to data limitations and are made with low confidence. Attribution of individual extreme weather events is challenging due to their rarity. Conflicting claims about the causes of the 2021 Western North America Heatwave illustrate the perils of hasty attribution claims about individual extreme events.

8.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) distinguishes between detection of climate change and attribution of its cause. As defined by the AR6 WGI Glossary (IPCC, 2025):

Detection: Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%.

Attribution: Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence.

Both detection and attribution rely on statistical analysis. Detection focuses on whether changes are significant enough to stand out from random variation regardless of cause. Attribution involves comparison of observed events to model-generated counterfactuals. Since experimentation on the climate is not possible, attribution requires statistical inference to assess how much human activities (such as GHG emissions) versus natural factors (like volcanic eruptions) contribute to observed changes. Attribution methods assume all external and internal drivers of the system are known and represented.

There are ongoing scientific debates around attribution methods, especially those for attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. AR4 Working Group I (Hegerl *et al.*, 2007) explained it as follows:

‘Attribution’ of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is ‘consistent with the estimated responses to the given combination of anthropogenic and natural forcing’ and ‘not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings’ (IPCC, 2001)... The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

AR5 Working Group II (Cramer *et al.*, 2014) makes the following statement:

Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

8.2 Attribution methods

The IPCC employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key IPCC attribution methods.

Optimal Fingerprinting uses linear regression to explain variations in observed climate data as a weighted sum of climate model simulations run with and without anthropogenic forcings. The data used in the regression model is weighted to try to minimize the influence of random noise and the estimation method is chosen to account for climate model error.

Time Series Analysis exploits statistical differences between anthropogenic forcing and natural variability to see which dominates observed temperatures and also uses variations in the timing of changes to determine if causal dependence across data series can be inferred.

Process-Based Attribution focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification

Extreme Event Attribution assesses the role of human influence in the likelihood of occurrence or intensity of extreme weather events (*e.g.* heat waves or droughts). Methods include:

- Probabilistic Event Attribution uses large ensembles of climate model simulations to compare observed events to model-generated counterfactuals
- Storyline Approach examines the physical processes driving an event and evaluates how anthropogenic forcings might have modified those processes

8.3 Attribution of global warming

Attribution statements for global warming in the three most recent IPCC Assessment reports are:

AR4: **Most of the observed increase** in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations. (IPCC 2007)

AR5: It is *extremely likely* that **more than half of the observed increase** in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human-induced contribution to warming is similar to the observed warming over this period. (IPCC 2013)

AR6: The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that **well-mixed GHGs were the main driver** of tropospheric warming since 1979. (IPCC 2021)

The AR4 and AR5 attribution statements reference the warming since the mid-20th century, the period when greenhouse gas emissions began increasing rapidly. The words “most” and “more than half” are deliberately imprecise, potentially ranging from 51 to 99 percent of the warming – presumably this imprecision is to account for structural uncertainties such as natural internal variability. The confidence level increases from *very likely* to *extremely likely* from AR4 to AR5. The structure of the attribution statement in the AR6 is fundamentally different, referencing the warming to the period 1850-1900. The AR6 attribution statement is more precise numerically, but with a lower level of confidence at “likely” – AR6 attributes essentially all the warming to increases in greenhouse gases. The most confident statement from AR6 relates to the tropospheric warming since 1979, using the words “main driver” and “*very likely*.”

There are three areas of substantive criticism of the IPCC’s assessment of the causes of the recent warming: inadequate assessment of natural climate variability, inappropriate statistical methods, and substantial discrepancies between models and observations. The last is discussed in Chapter 5, while this chapter discusses the first two factors. All of these criticisms are relevant to the IPCC’s policy-informing attribution of the recent warming, which also underpins extreme event attribution

8.3.1 Natural climate variability

AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by –0.1°C to +0.1°C, and internal variability has changed it by –0.2°C to +0.2°C – on average having essentially no net impact on the warming since 1850-1900. As discussed below, this minimal contribution of natural variability has been disputed by several publications that question the magnitudes of solar variability and internal variability from large-scale ocean circulations.

Solar variability

AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes over the period 1750–2011 was very small (0.05 W/m², Myrhe *et al.*, 2014). AR6 acknowledges substantially higher values and a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the twentieth century increased by 0.7–2.7 W/m², a range that includes both low and high variability TSI data

sets (Gulev, 2021). However, the recommended forcing dataset for the CMIP6 climate model simulations used in AR6 for attribution studies averages two data sets with low solar variability (Matthes, 2017).

While AR6 shows a substantially greater solar impact than does AR5, the overall impact of solar forcing on the climate was still assessed to be small compared to anthropogenic forcing. However, the impact of solar variations on the climate is uncertain and subject to substantial debate (Lockwood, 2012; Connolly *et al.*, 2021) - something that is not evident in the IPCC assessment reports.

The variations of TSI over time remains a challenging problem. Since 1978, there have been direct measurements of TSI from satellites. However, the data exhibits non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. There are several rival composite TSI datasets that disagree as to whether TSI increased or decreased during the period 1986–96 (the ACRIM gap; see Chapter 4). Further, the satellite record of TSI is used to calibrate proxy models that infer past solar variations from sunspots and cosmogenic isotope measurements (Velasco Herrera *et al.*, 2015).

There is substantial evidence for high solar activity in the second half of the 20th century (starting in 1959) and extending into the 1990's, before a decline in the early 21st century; this period is often termed the “Modern Maximum.” (Chatzistergos *et al.*, 2023; Solanki *et al.*, 2004; Usoskin *et al.*, 2007). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

This uncertainty causes some reconstructions of TSI from 1750 to have low variability (implying a very low impact of solar variations on global mean surface temperature) whereas datasets with high TSI variability can explain more than 70 percent of the temperature variability since preindustrial times (Scafetta, 2013; Stefani, 2021). The choice of TSI satellite record used in an analysis can therefore substantially influence how much climate change is attributed to human versus natural forcings.

There is growing evidence that other aspects of solar variability, which are referred to as solar indirect effects, either amplify TSI forcing or are independent of TSI forcing. Scafetta *et al.* (2023) suggests that ~80 percent of solar influence on climate might stem from non-TSI mechanisms. There are numerous candidate processes, including solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Such solar indirect effects are not included in climate models, although indirect methods of estimating their impacts suggest they are significant. However, claims of non-TSI mechanisms influencing climate are uncertain and debated.

Natural variability of large-scale ocean circulations

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns, including the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO). These circulations influence ocean heat uptake and heat distribution and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astronomical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability, most models have too little amplitude compared to observations at multi-decadal frequencies and phasing out-of-sync with the observed climate (Kravtsov *et al.* 2024). Averaging multiple simulations effectively averages out the internal variations, leaving only the forced climate variability (*e.g.* CO₂ forcing). With most of the modern warming beginning in the late 1970's, the recent 50-year warming is on the same time scale as the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the AR5 and AR6 reports:

AR5: Decadal variability in the Pacific, associated with the PDO or IPO [Interdecadal Pacific Oscillation], contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations.

AR6: Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (*high confidence*).

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: “The likely range of change due to internal variability is -0.2°C to $+0.2^{\circ}\text{C}$ (IPCC, 2021).” This implies a trough-to-peak change of 0.4°C . Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the past 50 years, when most of the recent warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual ensemble simulating a different phasing. Once the simulations of the ensemble members and different models are averaged, the natural internal variability contribution is averaged out owing to differences in phasing, effectively cancelling the role of natural internal variability in the attribution process.

The time series of global surface temperature anomalies since 1850 (Figure 8.1) shows irregular variations of significant amplitude against the background of an overall warming trend and, after 1976, a pronounced difference in trends between the Northern Hemisphere and the Southern Hemisphere. The period between 1905-1945 shows a strong trend of warming. The following 30 years from 1945-1976 showed slightly declining temperatures. The most recent warming period started in 1977.

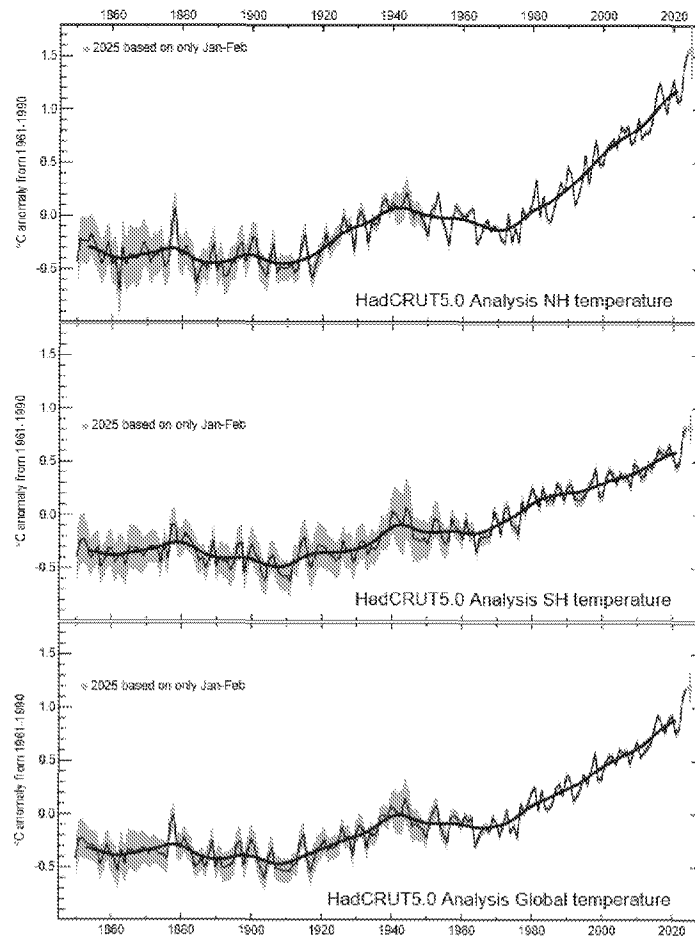


Figure 8.1 Global average surface temperature anomalies 1850—2025. Top: Northern hemisphere. Middle: Southern hemisphere. Bottom: Global average. Source: UK Hadley Centre [HYPERLINK "<https://crudata.uea.ac.uk/cru/data/temperature/HadCRUT5.0Analysis.pdf>"]

The causes of the early 20th century warming are discussed by Hegerl *et al.* (2017; 2019). The atmospheric CO₂ concentration increased from 298 ppm in 1905 to 310 ppm in 1941, implying that CO₂ had little impact. Volcanic activity during this period was very low, and solar forcing is uncertain. Yet Hegerl *et al.* (2017) somehow inferred that 40-54 percent of this warming could be attributed to external forcing, with the rest associated with internal variability. Bronniman *et al.* (2024) focused on the causes of the cooling in the first decade of the 20th century in the Southern Hemisphere. They found that the cooling was related to a La-Niña-like pattern in the Pacific, a cold tropical and subtropical South Atlantic, a cold extratropical South Pacific, and cool southern midlatitude land areas. The Southern Annular Mode was positive, with a strengthened Amundsen–Bellingshausen seas low, although the spread of the data products is considerable.

The warming in the 1930's and subsequent cooling during mid-century was particularly pronounced in the Arctic. Bokuchava and Semenov (2021) find that these variations were most likely caused by a combined effect of long-term natural climate variations in the North Atlantic and North Pacific with a contribution of the natural radiative forcing related to the reduced volcanic activity and variations of solar activity, as well as growing greenhouse gases concentrations. Tokinaga *et al.* (2017) showed that the combined effect of internally generated Pacific and Atlantic interdecadal variability intensified Arctic

warming in the early 20th century. The synchronized Pacific-Atlantic warming drastically alters planetary-scale circulations over the Northern Hemisphere; these same circulation patterns have a global influence.

The cooling period between 1945 and 1976 has been referred to as the “grand hiatus.” Numerous causes have been hypothesized: natural internal variability from fluctuations associated with the Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation; cooling from increased emissions of aerosols from industrial activities; increased heat uptake in the Atlantic, Southern and Equatorial Pacific Oceans. Thompson *et al.* (2010) find that the hemispheric differences in temperature trends in the middle of the twentieth century stem largely from a rapid drop in Northern Hemisphere sea surface temperatures of about 0.3 °C between about 1968 and 1972.

The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947–1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns, including the frequencies of El Niño and La Niña events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming. When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, 40 percent or more of the warming in the second half of the 20th century is attributed to natural internal variability (McLean *et al.*, 2009; Tung and Zhou, 2013; Chylek *et al.*, 2016; Scafetta, 2021).

8.3.2 Optimal fingerprinting

Optimal fingerprinting is a statistical technique introduced by Allen and Tett (1999) that compares observed climate data to climate model simulations to identify patterns (or “fingerprints”) associated with human or natural forcing. It involves taking a vector of observed climate changes, such as warming rates in locations around the world, and decomposing them into a weighted sum of “signals”, which are analogues to the observations generated by climate models with different types of forcings. The weights are chosen using a regression method called Total Least Squares (TLS). The analysis commonly uses just two signals, one generated by models using only anthropogenic forcings and one using only natural forcings. If the estimated weighting coefficient attached to a signal is significantly different from zero, then that signal is said to be “detected”. If it is close to 1.0, then the model generating the signal is said to be consistent with observations. If it is less than 1.0, then the model signal for that forcing is too strong and needs to be scaled down, and vice-versa. Both the observed data and the signals are weighted using a model-generated estimate of patterns of randomness in the climate system so as, in principle, to put maximum weight on regions where natural variability is minimized.

Optimal fingerprinting is the primary tool for attribution in the research literature. While it has been widely used and prominently featured by the IPCC since 2001, there is very little literature examining the statistical properties of the results it generates. One of its inherent weaknesses is that results depend on assumptions about the accuracy of climate models, especially regarding their representation of natural variability (IPCC AR5 Ch 10.2.3).

A series of papers by McKittrick (McKittrick 2021, 2022, 2023, 2025) has challenged the optimal fingerprinting method, arguing that it is inherently unreliable and that practices adopted from econometrics can provide more valid results. Statistical theory requires that for regression models to yield unbiased coefficients, a set of assumptions called the Gauss-Markov conditions must hold. McKittrick (2021) argued that the Allen and Tett (1999) methodology violates the Gauss-Markov conditions, leading to potentially biased and inconsistent fingerprinting coefficients, undermining the reliability of the method. Chen *et al.* (2023) confirmed this analysis, although they argued that the method could yield valid results under very stringent assumptions. McKittrick (2022) and (2023) raised a further concern that climate scientists—virtually alone among

scientific disciplines—have used TLS to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unstable unless some strong assumptions hold that in practice are unlikely to be true. Under conditions that easily arise in optimal fingerprinting, TLS estimates have a large positive bias. Thus, any study that used TLS for optimal fingerprinting without verifying its applicability in the specific data context has likely overstated the attribution.

McKittrick (2025) presented an empirical example comparing the results of conventional optimal fingerprinting against methods drawn from mainstream econometrics that are known to be valid for the specific application of signal detection. While the IPCC optimal fingerprinting method yields an anthropogenic signal coefficient close to 1.0 on a global temperature data set spanning 1900 to 2010, consistent estimation yields a coefficient around 0.4, which rises to about 0.65 on data spanning 1980 to 2010, implying the model response to greenhouse gases needs to be scaled down by about half to optimally match observations. The natural forcing signal coefficient, by contrast, is between 2.0 and 4.0, implying the climate model signals of natural forcing need to be scaled up two-to four-fold to match observed climate change. The fingerprinting coefficients estimated in McKittrick (2025), when used to scale the average sensitivity of the climate models used to generate the forcing signals in his data set, imply a Transient Climate Sensitivity of 1.4°C, which is consistent with the estimate by Lewis (2023) using a different estimation method and multiple independent data sets.

While these analyses do not falsify results of the IPCC optimal fingerprinting method, they do challenge the basis on which they were believed to be correct.

8.3.3 Time series methods

The IPCC (AR5 WGI 10.2.2) drew attention to alternative approaches of assessing causality that emerged from the time series econometrics literature. These have the advantage of not depending on assumptions about the accuracy of climate models, but the disadvantage that they depend on difficult-to-test assumptions about the data generating process underlying climate and forcing data. The methods, now referred to as climate econometrics, use the tools of unit root testing, Granger causality and cointegration analysis, all of which are familiar in economics and finance and which are slowly being adopted in climate science. Time series analysis methods hold out the possibility of determining whether anthropogenic or natural forcings are the primary drivers of climate change without requiring the use of climate models, although key questions remain unsettled (e.g. Dergiades *et al.*, 2016, Balcombe *et al.*, 2019, Dagsvik *et al.*, 2020, Razzak, 2022, Dagsvik and Moen, 2023).

“Granger causality” modeling is a tool for determining directions of influence in data series that move together. It is a statistical, not a physical, concept. If knowing the current value of one variable significantly improves the forecast accuracy of another variable, we can infer a causal connection exists; this is called Granger causality. The modeling tools, called vector autoregression, measure direct impulse-response patterns and feedbacks. An application to the well-known Vostok ice core data revealed an error in Al Gore’s documentary *An Inconvenient Truth*. Gore showed the data and drew attention to the coherence of temperature and CO₂ changes over a 440,000 year span, which he asserted was due to CO₂ driving temperature changes. But temperature changes can also affect atmospheric CO₂ levels. Davidson *et al.* (2015) examined the series and found that temperature Granger causes CO₂ but not the reverse. In other words on the time scales represented in the Vostok data, the coherence in the series is primarily due to the influence of temperature on CO₂ levels, not the feedback of CO₂ levels on temperature.

In summary, the primary statistical methods for attributing causation in climate data are optimal fingerprinting and time series analysis. Applications of the Allen and Tett (1999) optimal fingerprinting method dominate the attribution literature and have underpinned past IPCC conclusions, but results depend on the accuracy of climate models and the method has recently been criticized as inherently biased. Time

series methods do not depend on climate models but require assumptions of their own and have generated results that have thus far not converged on a consensus.

8.4 Declining planetary albedo and recent record warmth

A sharp recent increase in global average temperatures has raised the question of short-term drivers of climate. One such candidate is the fraction of absorbed solar radiation which has also increased abruptly in recent years. The question is whether the change is an internal feedback to warming caused by greenhouse gases, or whether something else increased the fraction of absorbed radiation which then caused the recent warming.

The planetary albedo is the fraction of incoming solar radiation that is reflected back into space rather than being absorbed by the planet. Highly reflective surfaces like cloud tops and snow and ice are most important in this regard. The Earth's albedo is approximately 30 percent, meaning almost a third of the sunlight that reaches Earth is directly reflected back to space. A lower albedo implies more solar energy is absorbed by the planet to be then re-radiated as heat. Hence, other things being equal, a decline in planetary albedo is associated with a warming of the Earth.

Arguably the most striking change in the Earth's climate system during the 21st century is a significant reduction in planetary albedo since 2015, which has coincided with at least two years of record global warmth. Figure 8.2 shows the planetary albedo variations since 2000, when there are good satellite observations. The 0.5 percent reduction in planetary albedo since 2015 corresponds to an increase of 1.7 W/m² in absorbed solar radiation averaged over the planet (Hansen and Karecha, 2025). For comparison, the IPCC estimate of forcing from the increase in atmospheric CO₂ compared to preindustrial times is approximately 2.2 W/m² (Figure 3.1.2).

Looking back prior to 2000 with less adequate data, Goessling *et al.* (2025) assessed that the planetary albedo was relatively low around the 1940's and 50's before rising industrial aerosol precursor emissions increased the albedo until the 1980's. The strongest planetary albedo excursions were high-albedo episodes caused by volcanic eruptions, such as after the Mount Pinatubo eruption in 1991. Although uncertain, the 2023 planetary albedo minimum might have been the lowest since at least 1940.

Changes in surface characteristics cannot explain this decrease in planetary albedo since 2015:

- Arctic sea ice extent has declined by about 5 percent since 1980 (https://nsidc.org/data/seaice_index/images/s_plot_hires.png), although following 2007 there has been a pause in the Arctic sea ice decline (England *et al.*, 2025)
- Regarding Antarctic sea ice, the IPCC AR6 concludes that "There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability." (Summary for Policymakers, A.1.5)
- Northern hemispheric annual snow cover has been slowly declining since 1967, with barely significant trends. The data show the Northern Hemisphere has snowier winters, accompanied by more rapid melt in spring and summer, see [[HYPERLINK "http://climate.rutgers.edu/snowcover/"](http://climate.rutgers.edu/snowcover/)] and Section 5.6
- Global greening (Chapter 2) is contributing to the decrease in planetary albedo, as forests have a lower albedo than open lands or snow. However, there is some evidence that forests increase cloud cover (high reflectivity), which counteracts the direct albedo decrease associated with increasing forested area.

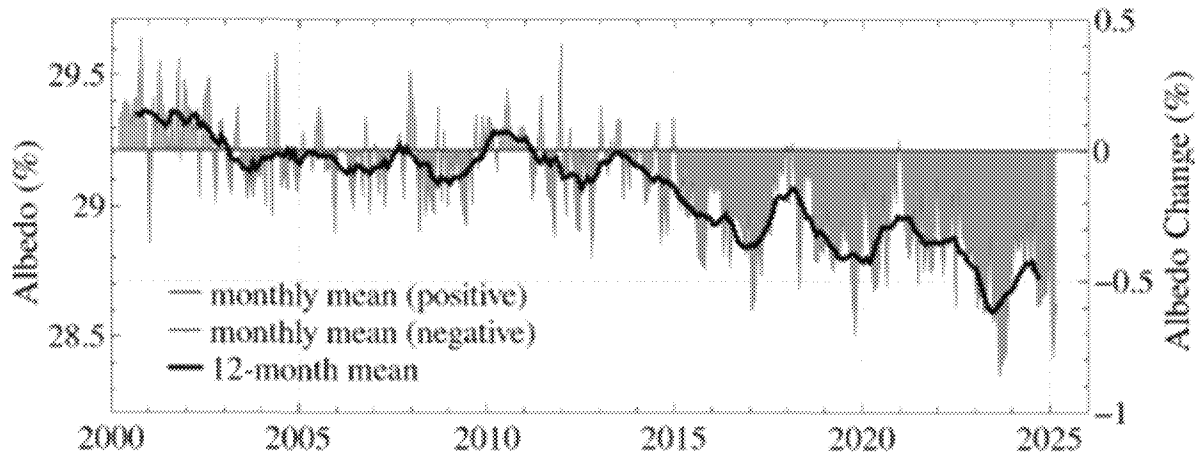


Figure 8.2. Earth's albedo (reflectivity, in percent), with seasonality removed. From Hansen and Karecha (2025)

Changes in surface reflectivity are contributing to a small, slow decline in planetary albedo. However, these changes cannot explain the sharp decline in planetary albedo beginning in 2015. Further, any changes in surface albedo are effectively damped by about a factor of three on average, primarily due to cloud masking (Loeb *et al.* 2019). Surface albedo changes have thus contributed only weakly to the recent planetary albedo decline, particularly when averaged annually and globally. This leaves the most likely explanation for the sharp albedo decline as changes in atmospheric aerosols and/or clouds.

Aerosols are small particles in the atmosphere that reflect sunlight and can interact with cloud processes to make the clouds more reflective. Aerosols have both natural origins (*e.g.* dust from soils, wildfires) as well as human origins from combustion (including fossil fuels). Regions that are greening and/or have an increase in rainfall might produce less dust. For anthropogenic aerosols, new ship fuel regulations aimed at reducing sulfur emissions were implemented in three phases, in 2010, 2015 and 2020. Sulfate particles reflect solar radiation. Cleaner air means less solar radiation is reflected, which contributes to surface warming. Indirect effects of sulfate aerosols include increasing the reflectivity of low-level clouds in the subtropics. There is controversy surrounding the importance of this change in sulfate emissions to the Earth's radiation balance (Hodnebrog *et al.*, 2024; Yuan *et al.*, 2024), but the restriction of this effect to major shipping routes suggests a small global impact (Schmidt, 2024).

Changes in clouds are the primary candidate to explain the decline in global albedo since 2015. Two recent papers (Loeb *et al.*, 2024; Goessling *et al.* 2024) have addressed recent variations in cloud properties. By considering satellite and reanalysis data, Loeb *et al.* found that decreases in low- and mid-level clouds since 2015 are the primary reason for decreasing planetary albedo in the Northern hemisphere, whereas in the Southern hemisphere the decrease in planetary albedo is primarily due to decreases in mid-level clouds across all latitude zones. Goessling *et al.* (2024) found that cloud anomalies were mainly due to reduced low-level clouds. Regions with coherent low-level cloud reductions over the past decade include the warm pool region around the Maritime Continent and the northern extratropical western Pacific, as well as large parts of the Atlantic and adjacent land regions. The reduction of global cloud cover identified in these analyses since 2015 is 1-2 percent.

The issue then becomes the cause of the change in cloud cover. Two explanations have been posited for the declining cloud cover over the past decade:

- Natural climate variability

- Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha, 2025)

It is not easy to justify a new positive low cloud feedback that began emerging in 2015. However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds:

- The 2014-2016 was one of the strongest El Niño events on record
- A cold anomaly beginning in 2015 in the subpolar gyre of the North Atlantic reflects a shift in the ocean circulation pattern associated with decadal variability in the Atlantic (Frajka-Williams *et al.*, 2017; Arthun *et al.* 2021).
- The Pacific Decadal Oscillation positive index peaked in 2016, then declined and has been in negative territory since late 2019
- Eruption of the submarine Hunga-Tonga volcano in 2022

Interannual cloud anomalies associated with the El Niño Southern Oscillation (ENSO) have a significant global signal and strong regional signals, especially over the tropical Indian and Pacific Oceans.

The Hunga Tonga eruption is remarkable in its coincidence with the exceptionally low value of planetary albedo in 2023. Goessling *et al.* (2024) found that the cloud perturbations in 2023 showed a different pattern from the overall pattern since 2015, with reduced cloud cover being most pronounced in the northern hemisphere and tropics. Regional reductions in cloud cover were most pronounced over the eastern Indian Ocean, over South America and extending over the eastern Pacific, as well as over northern North America, in the Southern Ocean around 60S, in the subtropical and eastern North Atlantic, and in parts of the North Pacific.

The Hunga Tonga eruption was unusual in that it injected large amounts of water vapor into the stratosphere in addition to sulfate particles. Early publications focused on the impacts to stratospheric circulations and the direct radiative impact. In 2025, papers are emerging that examine the indirect effects of Hunga Tonga on surface climate using ensemble simulations from earth system models (Bednarz *et al.*, 2025; Kuchar *et al.*, 2025). These papers found statistically significant impacts on regional climates that were driven by circulation changes from couplings between the stratosphere and troposphere. These papers indicate the complex interactions between volcanic activity and climate dynamics. More research is needed to untangle any impacts of the Hunga Tonga eruption on the planetary albedo.

In summary, the decline in planetary albedo and the concurrent decline in cloudiness have emphasized the importance of clouds and their variations to global climate variability and change. A change of 1- 2 percent in global cloud cover has a greater radiative impact on the climate than the direct radiative effect of doubling CO₂. While it is difficult to untangle causes of the recent trend, the competing explanations for the cause of the declining cloud cover have substantial implications for assessing the Equilibrium Climate Sensitivity and for the attribution of the recent warming. An additional 10 years of data should help clarify whether this is a strong positive cloud feedback associated with warming or a temporary fluctuation driven by natural variability

8.5 Attribution of climate impact drivers

The IPCC (Ranasinghe *et al.* 2021) defines “climate impact drivers” or CIDs as “physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems.” Hence CIDs are those features of the weather and climate system of primary interest in assessing the impacts of climate change since they potentially affect humans and the natural world. For instance, under the heading “Heat and Cold,” CIDs are identified as mean air temperature, extreme heat, cold spells and frost. The IPCC

also points out that CIDs are not necessarily harm-related: depending on the system in question they can be detrimental, neutral, beneficial or a combination.

The first columns Table 12.12 in Ranasinghe *et al.* (2021, p. 1856), reproduced here as Table 8.1, summarize the AR6 assessment of whether a signal of attributable anthropogenic influence has emerged across all major CIDs. One of the themes of this chapter is that attribution methods used by the IPCC tend to overstate the anthropogenic influence and understate the role of natural variability. Nonetheless a striking feature of that summary table is how few CIDs exhibit an anthropogenic signal sufficient to distinguish them from natural variability.

Out of the 33 weather impact categories listed, an anthropogenic signal is asserted with *high confidence* in only five, and with *medium confidence* in a further four. (Note that one of the CIDs is an increase in CO₂ levels, and since it is a tautology to attribute this to increased CO₂ levels this CID can be ignored.) For the rest the IPCC does not claim to have detected anthropogenic drivers. Of the five *high confidence* assertions, two are for changes in average temperatures (air and ocean) hence are not measures of extreme weather. Further, two of the four *medium confidence* assertions are related to ocean chemistry and thus are likewise not related to extreme weather. The IPCC does not assert a human influence on many non-temperature weather features such as wind, precipitation, flooding, or drought.

Other columns of IPCC Table 12.12 report on whether anthropogenic signals are expected to emerge this century under RCP8.5, the most extreme forcing scenario. We have omitted these columns for several reasons. First, because they refer to whether climate models project detectable signals in the observations, which is a very different question than our concern here: whether a signal has been detected in historical data. Second, as we discuss in Chapter 4, the RCP8.5 scenario is a misleading and implausible high-end storyline, it is not a “base case” or business-as-usual projection. Third, the ensemble of detailed models is acknowledged (Palmer and Stevens 2019) to be “not fit for purpose” in describing regional changes and “unable to represent future conditions at the degree of spatial, temporal, and probabilistic precision with which projections are often provided.” (Nissan et al, 2019). Even with these caveats, we note that the omitted columns in AR6 Table 12.12 show most weather impacts are not expected to exhibit an anthropogenic signal through the end of this century.

Climatic Impact-driver Type	Climatic Impact-driver Category	Already Emerged in Historical Period
Heat and Cold	Mean air temperature	1
	Extreme heat	2
	Cold spell	4
	Frost	
Wet and Dry	Mean precipitation	
	River flood	
	Heavy precipitation and pluvial flood	
	Landslide	
	Aridity	
	Hydrological drought	
	Agricultural and ecological drought	
	Fire weather	
Wind	Mean wind speed	
	Severe wind storm	
	Tropical cyclone	
	Sand and dust storm	
Snow and Ice	Snow, glacier and ice sheet	
	Permafrost	
	Lake, river and sea ice	11
	Heavy snowfall and ice storm	
	Hail	
	Snow avalanche	
Coastal	Relative sea level	
	Coastal flood	
	Coastal erosion	
Open Ocean	Mean ocean temperature	
	Marine heatwave	
	Ocean acidity	
	Ocean salinity	13
	Dissolved oxygen	14
Other	Air pollution weather	
	Atmospheric CO ₂ at surface	
	Radiation at surface	

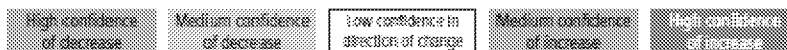


Table 8.1: Reproduction of column 1 of Table 12.12, IPCC AR6 Working Group I report. Emergence of anthropogenic signal in historical period for CIDs shown. White: no signal detected. Blue and orange: change detected (decrease or increase) and confidence level as indicated in color legend.

As discussed in Chapter 6 natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trend reversals over time. Table 8.1 makes the related point that it is not currently possible to attribute changes in most extreme weather types to human influences. Taking wind as an example, the IPCC claims that an anthropogenic signal has not emerged in average wind speeds, severe windstorms, tropical cyclones or sand and dust storms, nor is one expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather.

8.6 Extreme event attribution (EEA)

Examining the IPCC's treatment of extreme weather and climate event attribution more broadly, AR6 provides an ambiguous assessment of the role of anthropogenic warming that differs between its chapters. Chapter 11 of WG1 states (Seneviratne *et al.*, 2021):

Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system.

By contrast, as noted in Section 8.5, Chapter 12 of WG1 (Table 12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions (Ranasinghe, 2021):

- High confidence in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere
- Medium confidence in a decrease in extreme cold events in Australia, Africa and most of northern South America where observations allow trend estimation
- No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones

While the overall issue of detecting changes in extreme weather events and their attribution remains ambiguous, most of the activity in this area relates to the attribution of particular extreme weather events. The most prominent effort is World Weather Attribution (WWA; worldweatherattribution.org), an international research initiative for extreme event attribution that purports to analyze how climate change influences the likelihood and intensity of extreme weather events. Their approach is to use large ensembles of regional climate models to compare an event in today's climate with one in a counterfactual pre-industrial climate without human influences.

WWA has a prominent public presence in linking extreme weather to climate change, with its press releases attracting considerable attention in public and policy discussions. However, the WWA's extensive promotion of non-peer-reviewed findings, its open admission to shaping analyses to serve litigation, and its methodological challenges have sparked controversies, with critics questioning the robustness and impartiality of their conclusions (Pielke Jr. 2024). Despite these issues, WWA's work continues to influence climate science and media narratives. Technical criticisms of the approach include a lack of a formal detection process; an implicit assumption that 100 percent of the post-industrial warming is caused by greenhouse gases; and a failure to adequately account for internal climate variability.

Because EEA is relatively new, many basic methodological issues have yet to be settled in the expert literature. An important challenge is the lack of data. Extreme events are by definition rare. Many analyses of extreme event types (including the U.S. National Assessment Reports) only evaluate data since 1950 or 1970. However, as emphasized by Chapter 6, many of the worst extreme weather and climate events in U.S. history occurred in the first half of the 20th century, including in the early 19th century. And if paleoclimate reconstructions are considered, it becomes very difficult for an event to pass thresholds of what is expected from natural variability, particularly if a reasonably sized geographic region is considered.

Another challenge is defining the event under study. There is a longstanding literature in statistics and econometrics on the challenge of analyzing data with outliers. The issue arises because a data series establishes a probability distribution defining the expected range of observations. If an outlier is observed it might indicate that the underlying process giving rise to the data distribution has changed (which in the weather context would mean that a climate change has been detected) or that the underlying process has multiple regimes each with a different probability distribution, in which case observing an outlier simply means we were temporarily in a different regime, but the system itself was unchanged. If a time series contains only a single outlier event at the end of the series it is not possible to determine which model is the correct one (Chen and Liu 1993). For instance, there might be an “ordinary” weather regime that yields a distribution of summer daytime highs in a particular coastal region, and a second “heatwave” regime that kicks in when an inland blocking event occurs, which yields a temperature distribution centered 15°C higher than the first one. A day with temperatures 13°C above normal would either be an extreme heat anomaly under the first regime or a somewhat cool event under the second, and we have no way in this case of knowing on statistical grounds which view is correct.

Visser and Petersen (2012) and Sardeshmukh *et al.* (2015) both point out that different distributions might fit observed data equally well but yield very different implications about the likelihood of a specific weather event. Visser and Petersen argue that, in view of the deep uncertainties of extreme weather analysis, drawing a connection between individual events and global climate change should be avoided. Furthermore, the existence of an outlier at the end of a data series poses the problem that estimates of the event probabilities will be biased whether the outlier is included or excluded (Barlow *et al.*, 2020). Methods to eliminate the bias have not yet been established, leading some experts (*e.g.* Miralles and Davison 2023) to argue that in settings in which a data series contains a single extreme event at the end, estimation of a return period for the extreme event will be so biased and uncertain that it should be avoided altogether.

We provide a case study of a recent high impact extreme event in the U.S. to illustrate the challenges and ambiguities in attributing the frequency and intensity of extreme weather events to human-caused warming.

8.6.1 Case study – 2021 Western North America heat wave

The 2021 Western North America heat wave was an extreme event that affected much of Western North America in late June 2021. Surface temperature records were set in Portland, OR (116°F; previous record 107°F) and Seattle, WA (108 °F; previous record 103°F) (Mass *et al.*, 2024).

The WWA team generated international headlines with their analysis, which provided the following attribution statements (WWA, 2021; Philip *et al.*, 2022):

- Based on observations and modeling, the occurrence of this heatwave was virtually impossible without human-caused climate change.
- The event is estimated to be about a one in 1000-year event in today’s climate.
- The event would have been at least 150 times rarer without human-induced climate change.
- This heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).

But an important counter to the first claim is that other researchers concluded from historical weather data that while a heat wave of the magnitude observed was indeed virtually impossible without anthropogenic climate change, it was also virtually impossible *with* climate change. Bercos-Hickey (2022) noted “these temperatures were virtually impossible under any previously experienced meteorological conditions, with or without global warming.” McKinnon and Simpson (2022) stated “the most likely explanation remains that the weather event itself was ‘bad luck.’” The 2023 Oregon Climate Assessment (Fleischman, 2023) concluded that the heat dome would have formed even without climate change and “There is no evidence that the highly unusual combination of weather features that drove the heat dome were made more likely by climate change, and climate models do not project an increase in the frequency of high-pressure ridges over the Pacific Northwest” (Fleischman, 2023, p. 49).

Mass *et al.* (2024) summarizes the proximate sequence of compound events leading to the heat wave. There was a record-breaking mid-tropospheric ridge over the Pacific Northwest, forced by a tropical disturbance in the western Pacific. This produced record-breaking mid-tropospheric temperatures, strong subsidence in the lower atmosphere, low-level easterly flow that produced downslope warming on regional terrain and the removal of cooler marine air, and an approaching low-level trough that enhanced downslope flow. The event occurred at a time of maximum solar insolation, and drier-than-normal soil moisture. Using a storyline approach, Mass *et al.* assessed that there was no trend in drought and dry soils in the Pacific Northwest; there is no evidence of global warming producing stronger ridges of high pressure, and no observed trend in heat waves or record temperatures in the region. They concluded that although anthropogenic warming might have contributed as much as 2°F to the magnitude of the event, there is little evidence of further amplification of the event from increasing greenhouse gases.

Bercos-Hickey *et al.* (2022) conducted a statistical analysis of a model-based attribution study of this heat wave. Because the event is a far outlier and far above the bounds of Generalized Extreme Value distributions fitted from historical data, they concluded that estimates of return times, quantitative changes in event magnitude and frequency, and probability of the extreme temperatures such as provided by the WWA are not accurate and should be interpreted as having low confidence. They found that hindcast attribution methods using an ensemble of regional climate models, combined with Pearl (2009) causal inferences, can provide limited and conditional information about the magnitude of the human influence on this heatwave - they provided a more highly constrained estimate that human activities caused a ~1.4°F–1.8°F increase in the daily maximum temperatures.

Zeder *et al.* (2023) also concluded that the methods employed by Philip *et al.* (2022, the WWA analysis) tend to overstate the rarity of extreme heat waves, leading to a biased perception of the effect of climate change on the heatwave event: “The tendency to overestimate the return period of observed extreme heatwave events may fuel the impression that seemingly impossible heatwave extremes are currently clustering at an unprecedented rate.”

The 2021 Western North America heatwave was a rare and unprecedented compound weather event that broke century-old temperature records by as much as 9°F. While the WWA team received worldwide publicity for their rapid attribution claims blaming anthropogenic climate change, subsequent peer-reviewed analyses showed that the event was caused by rare meteorological conditions that were not made more probable by global warming.

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PART III: IMPACTS ON ECOSYSTEMS AND SOCIETY

9 CLIMATE CHANGE AND U.S. AGRICULTURE

Chapter summary

There has been abundant evidence going back decades that rising CO₂ levels benefit plants, including agricultural crops, and that CO₂-induced warming will be a net benefit to U.S. agriculture. The increase in ambient CO₂ has also boosted productivity of all major U.S. crop types. Various attempts to argue that CO₂-induced warming will harm agriculture do not hold up under scrutiny.

9.1 Econometric analyses

Econometric analyses of the effects of climate change on agriculture have sought to integrate information about long term crop yield changes in response to temperature and precipitation changes under assumptions about adaptive behavior by farmers. One method focuses on variations in agricultural land values. The rationale is that if climate change is a long-term net benefit for agriculture it should be capitalized into higher market values for agricultural land, and vice versa. While individual crops might benefit from, or be harmed by, climate change, once the adaptive responses of farmers are considered the value of farmland represents an index of whether the changes are expected to be beneficial or not. Mendelsohn *et al.* (1994) examined the relationship between historical climatic variations on agricultural land values and concluded global warming would be slightly beneficial to American agriculture.

The Mendelsohn *et al.* method, called Ricardian analysis after David Ricardo, the 19th century British economist who pioneered the study of land values, attracted subsequent criticism from authors who argued it failed to account for differences in land values attributable to fixed locational characteristics like soil quality, and non-climatic changes including nearby urbanization. Deschênes and Greenstone (2007) looked at agricultural profits instead of land values and reached conclusions similar to Mendelsohn *et al.* (1994), namely that past climatic variations had relatively little effect on farm profitability and that warming would likely yield small overall benefits for the U.S. agricultural sector. However, a subsequent exchange with critics led them (Deschênes and Greenstone 2012) to revise their conclusions and project potentially large losses in U.S. agriculture due to climate warming.

Burke and Emerick (2016) looked at temperature variations over 1980 to 2000 and argued that farmers were not as able to adapt to temperature changes as the Ricardian method assumes and that climate change would have large negative impacts on corn and soy yields. Schlenker and Roberts (2009) similarly argued that yield gains to past warming would not carry over to the future and corn and soy yields would sharply decrease this century due to climate change.

Two recent studies have argued that pessimistic findings such as these are not robust. Ortiz-Bobea (2019) argued that land values aggregate farm and non-farm influences and the latter need to be filtered out. He developed a data set using cash rents for agricultural activity as a measure of land value specifically for farming activity. Whereas the land value model implied future losses under climate warming, the same model estimated using cash rents did not, leading the author to conclude the pessimistic results were due to using an inaccurate measure of the returns to farming activity. Bareille and Chakir (2023) assembled a large data base on farm sale prices in France for properties that sold twice between 1996 and 2019. They could replicate pessimistic results showing negative effects of warming on agricultural land values using conventional econometric modeling. But by taking advantage of the repeat sales data, which provides information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture. The authors concluded that, taking adaptation into account, a warming climate would yield positive benefits for French agriculture that were between two and

20 times larger than had previously been estimated. On average, with full adaptation, they concluded that climate changes under the medium RCP4.5 scenario could double the value of French farmland by 2100.

A major deficiency of all these studies, however, is that they omit the role of CO₂ fertilization. Climate change as it relates to this report is caused by GHG emissions, chiefly CO₂. The econometric analyses referenced above focus only on temperature and precipitation changes and do not take account of the beneficial growth effect of the additional CO₂ that drives them. As explained in Chapter 2, CO₂ is a major driver of plant growth, so this omission biases the analysis towards underestimation of the benefits of climate change to agriculture.

9.2 Field studies of CO₂ enrichment

One of the ways the effect of CO₂ on crop growth has been studied is through “free air enrichment experiments” or FACE plots, in which small sources of CO₂ are placed in fields surrounding plants and the growth response to elevated CO₂ under varying weather conditions are recorded. Ainsworth *et al.* (2020) summarizes results from about 250 such studies. They found that elevation of CO₂ by 200 ppm caused an average 18 percent increase in crop yield in C3 plants. C4 plants exhibited benefits mainly under drought conditions.

In addition to FACE plot experiments there have been thousands of laboratory experiments on the effects of CO₂ on all kinds of plant growth. Here we review some of the results on key U.S. agricultural crops.

Soybean

Studies on the impact of elevated CO₂ on Soybean (*Glycine max* (L.) Merr.) plants in the water-deficient region of Huang-Huai-Hai Plain, China, showed that elevated CO₂ concentrations improved photosynthesis rate, water use efficiency, and growth Li (2013) under both normal conditions and drought conditions. The CO2Science.org website reports on 108 published experiments between 1985 and 2019 exposing soybean to enriched CO₂ levels. Converted to a +300ppm common scale the average growth benefit was +50.9 percent. There were also ten studies reporting on +600 ppm CO₂ enrichment, which increased photosynthesis by an average of 90.3%.

Maize (corn)

The CO2Science.org website reports on 28 published experiments between 1983 and 2018 exposing corn (*Zea mays* L.) to enriched CO₂ levels. Converted to a +300ppm common scale the average growth benefit was +23.7 percent. Corn also benefits from increased drought tolerance under elevated CO₂. An experimental study (Allen Jr., 2011) exposed plants to water stress conditions in sunlit controlled-environment chambers at 360 ppm (ambient) and 720 ppm (elevated) CO₂. The drought stress caused a 41 percent loss of growth under ambient CO₂ but only a 13 percent loss under elevated CO₂.

Wheat

The CO2Science.org website reports on 92 published experiments between 1983 and 2020 exposing common wheat (*Triticum aestivum* L.) to enriched CO₂ levels. Converted to a +300ppm common scale the average growth benefit was +67.6 percent. Blandino (2020) measured both the yield and nutritional quality of an “improver” hybrid wheat variety and its parents under elevated CO₂ levels (+166 ppm). They reported a grain yield increase of +16 percent but a 7 percent decrease in grain protein levels. But they also found that the food quality of different wheat varieties responded differently to elevated CO₂ levels, so that with proper varietal selection, growers could select wheat types that best take advantage of the elevated CO₂.

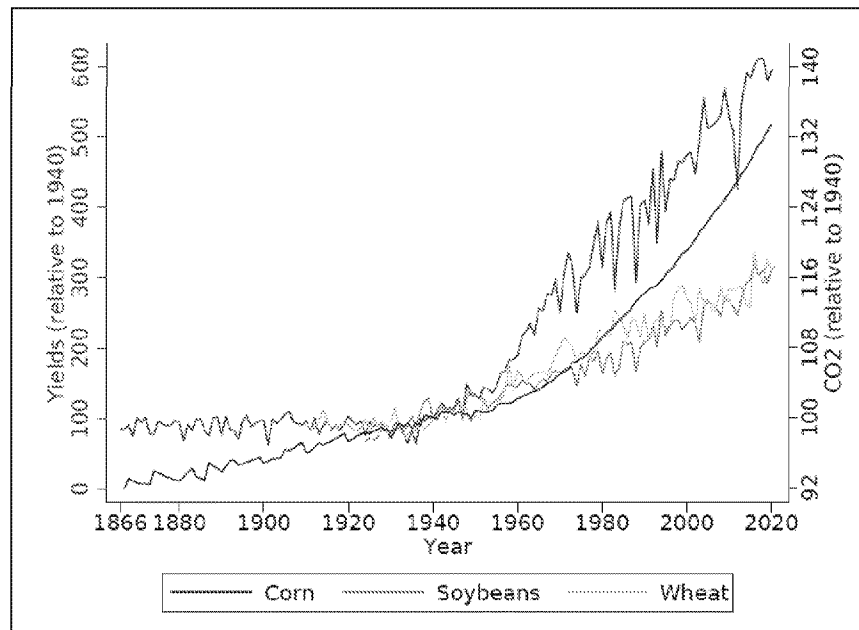


Figure 9.1: U.S. average CO₂ levels and yields of corn, soy and wheat all normalized so 1940=100. Source: Taylor and Schlenker (2021)

Further evidence

A 2021 report from the U.S. National Bureau of Economic Research (Taylor and Schlenker 2021) used satellite-measured observations of outdoor CO₂ levels across the United States, matched to county-level agricultural output data and other economic variables. After controlling for the effects of weather, pollution and technology the authors concluded that CO₂ emissions had boosted U.S. crop production since 1940 by 50 to 80 percent, attributing much larger gains than had previously been estimated using FACE experiments. They found that every ppm of increase in CO₂ concentration boosts corn yields by 0.5 percent, soybeans by 0.6 percent, and wheat by 0.8 percent.

Beyond growth benefits, extra CO₂ boosts plant resilience to dryness. Deryng *et al.* (2016) surveyed evidence on crop water productivity (CWP, the yield per unit of water used), drawing attention to the potential for CO₂ both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data on crop yield changes for maize (corn), wheat, rice and soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO₂ fertilization predicted CWP losses but CO₂ fertilization more than offset them; once fertilization was taken into account, all regions showed a net CWP gain. Deryng *et al.* also reported that negative yield impacts on wheat and soybean were fully offset by CWP gains and mitigated by up to 90 percent for rice and 60 percent for maize. Similarly, Cheng *et al.* (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO₂ uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryng *et al.* (2016) assumed that climate change would “exacerbate water scarcity”. It is noteworthy that while models predict drylands will expand under climate warming, observations show the opposite: greening is happening even in arid areas. Zhang *et al.* (2024) report that due to increased CO₂ levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”; increased desertification will happen in at most 4 percent of currently arid areas.

9.3 Crop modeling meta-analyses

Notwithstanding the abundant evidence for the direct benefits of CO₂ and of CO₂-induced warming on crop growth, in 2023 the U.S. Environmental Protection Agency (EPA 2023) boosted its estimate of the Social Cost of Carbon (SCC) about five-fold based largely on a very pessimistic 2017 estimate of global agricultural damages from climate warming (Moore *et al.*, 2017). One of the two damage models used by the EPA attributed nearly half of the 2030 SCC to projected global agricultural damages based on the Moore *et al.* (2017) analysis. This study was a meta-analysis of crop model studies simulating yield changes for agricultural crops under various climate warming scenarios. Moore *et al.* projected declining global crop yields for all crop types in all regions due to warming.

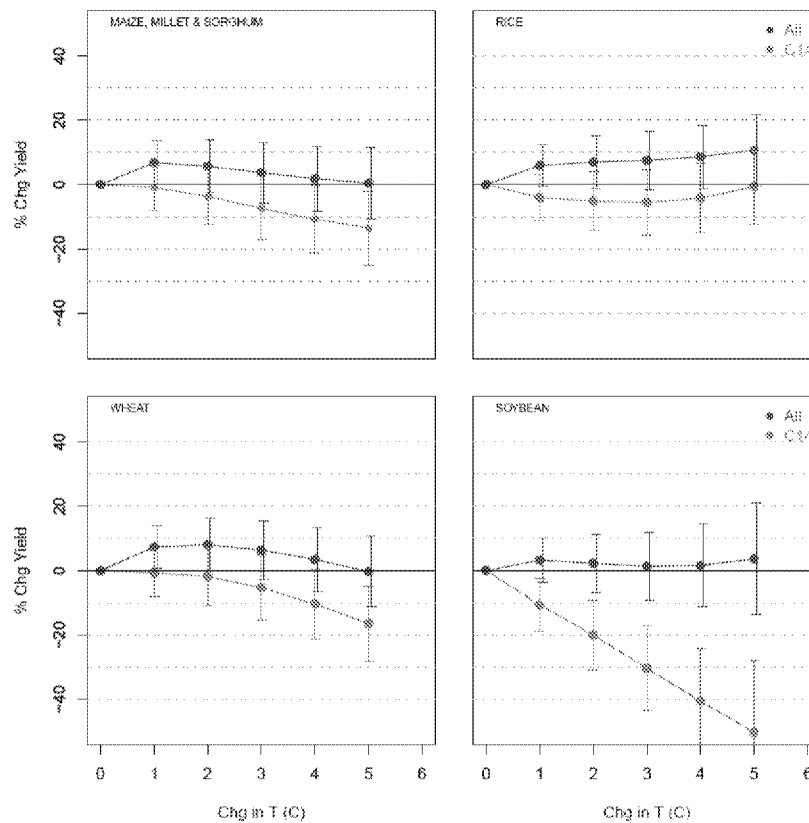


Figure 9.2 Crop yields under CO₂-induced climate warming. Blue: as published in Moore *et al.* (2017). Green: after including omitted data. Source: McKittrick (2025).

McKittrick (2025) re-examined the Moore *et al.* database and found that, while it claimed to cover 1,722 studies, only half the entries ($N=862$) had complete records, so that the sample available for regression analysis was much smaller than both studies indicated. McKittrick noted that the records most commonly missing were the changes in ambient CO₂ and found that in many cases these could be recovered from the underlying studies or the original climate scenario tables, thereby increasing the usable sample size by 40 percent. The crop yield projections incorporating the newly available data changed considerably. As shown in Figure 9.2, whereas the partial data set implied warming would decrease yield (blue lines), the complete data set implied constant or increase global yields, even out to 5°C warming (green lines).

9.4 CO₂ fertilization and nutrient loss

Evidence has shown that CO₂-induced biomass gains are sometimes accompanied by reductions in the concentrations of protein and other key nutrients such as iron and zinc (Ebi *et al.* 2021). Some experimental evidence has shown that the rising temperatures expected to accompany higher CO₂ levels will offset this loss (Köhler *et al.* 2019) although the evidence for this is mixed, as is the evidence that nutrient dilution observed to date is attributable to higher CO₂ (Ziska 2022). If nutrient dilution does occur under rising CO₂ levels there are several adaptive strategies that could be pursued.

First, selective breeding to raise micronutrient content is already long established (Saltzman *et al.* 2017) and has proven to be a cost-effective agronomic strategy (Ebi *et al.* 2021). Strategies can include both conventional breeding and genetically-modified organisms. An example of the latter is Golden Rice, which contains elevated levels of beta-carotene to boost biosynthesis of vitamin A in the human body. Optimal strategies will be location-specific because they vary by crop, climate and soil type (Ebi *et al.* 2021). Second, fortification of food products with micronutrients is already routine. Folic acid (a B vitamin) is added to flour and many other foods; iodine is added to table salt, most commercial breakfast cereals are fortified with iron and numerous vitamins, *etc.* Third, dietary supplements in the form of multivitamin tablets are inexpensive, widely-available and routinely consumed.

One concern about reliance on adaptive strategies is whether they are feasible in low-income countries. Micronutrient deficiency is already a problem in the developing world and dietary supplements have proven to be an effective low-cost response (Ebi *et al.* 2021). It should also be noted the IPCC emission scenarios that generate high levels of warming do so on the basis of high levels of income growth. The SSP scenarios³ assume that, compared to 2005 levels, global per capita income will double by 2100 in the lowest growth case (SSP3), and in the highest emission case (SSP5) global per-capita income will grow nearly 16-fold. In that scenario even the poorest regions (Africa and the Middle East) end up with a per capita income of about US\$126,000, 70 percent higher than current U.S. per capita income (about US\$75,000). Consequently the same scenarios in which CO₂ levels increase the most are also those in which global poverty is largely eliminated, in which case all countries would be able to afford dietary supplements as necessary to address micronutrient deficiencies, if they arise and cannot be addressed using on-farm agricultural strategies.

In summary, there is abundant evidence going back decades that rising CO₂ levels benefit plants, including agricultural crops, and that CO₂-induced warming will be a net benefit to U.S. agriculture. To the extent nutrient dilution occurs there are mitigating strategies available that will need to be researched and adapted to local conditions.

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³ See compilation at [[HYPERLINK "https://ourworldindata.org/explorers/ipcc-scenarios?Metric=GDP&Sub-metric=Total+radiative+forcing&Region=Global&country=SSP1+-+Baseline~SSP2+-+Baseline~SSP3+-+Baseline~SSP4+-+Baseline~SSP5+-+Baseline"](https://ourworldindata.org/explorers/ipcc-scenarios?Metric=GDP&Sub-metric=Total+radiative+forcing&Region=Global&country=SSP1+-+Baseline~SSP2+-+Baseline~SSP3+-+Baseline~SSP4+-+Baseline~SSP5+-+Baseline)].

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10 MANAGING RISKS OF EXTREME WEATHER

Chapter summary

Trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. The U.S. economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages. Heat-related mortality risk has dropped substantially due to adaptive measures including the adoption of air conditioning, which relies on the availability of affordable energy. U.S. mortality risks even under extreme warming scenarios are not projected to increase if people are able to undertake adaptive responses.

10.1 Socioeconomic context

Risks from human-caused climate change are affected by natural weather and climate variability and are dominated by the exposure of wealth in coastal and other disaster-prone regions and vulnerabilities of poorer populations. The evolution of climate risk in the U.S. has been dominated by societal factors, rather than by changes to the actual weather and climate hazards. Deaths from weather disasters have decreased substantially since 1900, even as U.S. population grew from 76 million in 1900 to over 331 million in 2020 (Goklany 2011). For example, the Galveston hurricane killed over 8,000 people in 1900 (0.01 percent of the U.S. population), whereas the worst recent disaster, Hurricane Katrina in 2005, killed 1800 people (or 0.0006 percent of the U.S. population) (NOAA National Hurricane Center 2025; U.S. Census Bureau 2025).

Technological advances have substantially reduced losses from extreme weather events. Early warning systems, satellite monitoring, and improved weather forecasting have reduced deaths, although exact numbers are hard to quantify (Deryugina and Hsiang 2023). U.S. weather forecasting has been estimated to reduce losses from weather events with an annualized benefit of \$31.5B, protecting lives, property, and supporting agriculture and transportation (NRC 2010). Improved hurricane forecasts have reduced pre- and post-landfall spending, with annual per hurricane cost reductions estimated at \$5B (Molina and Rudik 2024).

Infrastructure improvements have contributed to substantial reductions in losses from extreme weather events. Building codes, such as those implemented in Florida after Hurricane Andrew (1992), have reduced losses by ensuring structures can withstand high winds and floods. Homes built after 2002 showed minimal damage during Hurricane Michael (2018), unlike older homes (FEMA 2020). Sea walls, like the Galveston Seawall, protect against wave action and storm surge. The New Orleans Hurricane and Storm Damage Risk Reduction System successfully mitigated storm surge during Hurricane Isaac (2012) (Battelle Memorial Institute 2013). Inland dams in the U.S. help control flooding by storing excess water during heavy rains. It is estimated that the Tennessee Valley Authority (TVA) dams prevent about \$309M in annual flood damage in the TVA region and along the Ohio and Mississippi Rivers (TVA, 2025). During

Hurricane Helene (2024), TVA’s strategies prevented approximately \$406M in potential damages (APPA 2024).

10.2 Data challenges

Since 1980, NOAA has provided a count of annual U.S. weather-related disasters that it estimates to have exceeded \$1 Billion (inflation adjusted), showing a substantial increase starting in 2008. NOAA and other government officials have cited the upward trend in the Billion Dollar Disaster series as evidence that climate change is making extreme weather worse (Pielke Jr., 2024). But over time, population and wealth have increased dramatically in the U.S., so when an extreme weather or climate event occurs, there is more damage even if there is no underlying trend in the frequency or intensity of extreme weather. Pielke Jr. (2024) demonstrates that losses per weather disaster as a proportion of GDP have decreased by about 80 percent since 1980, as shown in Figure 10.1. Pielke Jr. (2024) also argued that in addition to relying on opaque data sources and unreported adjustments, NOAA failed to normalize its Billion Dollar Disaster data series properly for changes in population exposure and wealth. In May 2025 NOAA announced it has withdrawn the Billion Dollar Disaster product from publication (Pielke Jr., 2025).

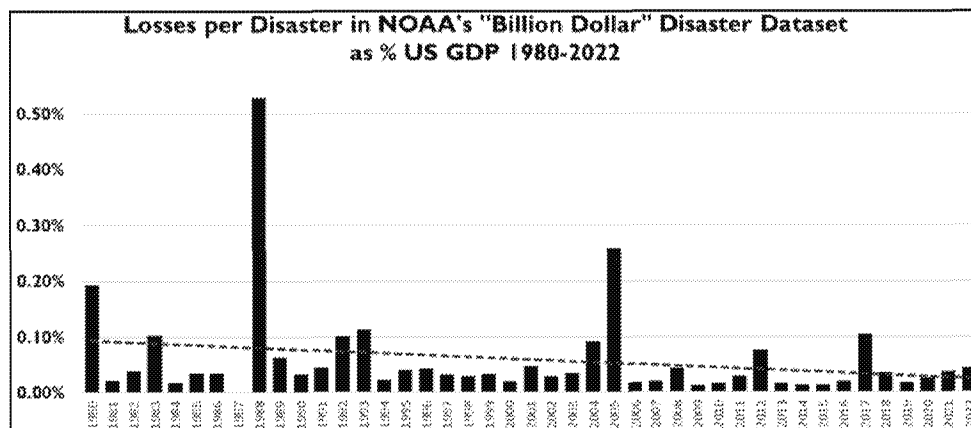


Figure 10.1: Losses per disaster as a % of Gross Domestic Product in NOAA’s billion-dollar disaster dataset (the version downloaded in July 2023), 1980 to 2022. Source: (Pielke, Jr. 2024)

In summary, trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. Finally, the U.S. economy’s expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages.

10.3 Mortality from temperature extremes

10.3.1 Heat and cold risks

Changes in temperature extremes are among the most certain impacts expected in a warming world. It stands to reason that extreme heat events would likely become more frequent while extreme cold events would become less frequent. This pattern is evident in the historical period, though not in the continental U.S. (Chapter 6), and is expected to continue with further warming.

Mortality during heat extremes is typically caused by heat stroke and heat exhaustion, while mortality during cold extremes typically stems from hypothermia and heart strain. Global mortality is substantially greater for cold conditions than for hot conditions (Zhao et al 2021, Ritchie 2024). Unlike with heat-related mortality, cold-weather risks set in even at moderately cold conditions (Gasparini *et al.* 2015, Lee and Dessler 2023). The U.S. EPA (citing data from the Centers for Disease Control) reports that on average over 1999 to 2015 there were 2.2 deaths per million Americans for which cold was listed as the main underlying cause and an additional 2.4 deaths per million for which cold was listed as a contributing factor (EPA 2025). By contrast there were 1.3 deaths per million for which heat was the main cause and an additional 0.8 per million for which it was a contributor. By this metric cold accounts for approximately double the weather-related deaths as does heat.

Epidemiological methods that consider correlational evidence, not just death certificate reports, indicate the cold/warm ratio might be much higher. A 13-country study of 74 million deaths from 1985 to 2012 estimated that, on average, 7.7 percent of deaths were attributable to sub-optimal temperatures, of which 7.4 percent were attributable to cold and only 0.4 percent were attributable to heat (Gasparini *et al.* 2015). In other words, cold weather killed 18.5 times as many people as did hot weather.

Figure 10.2 shows the distribution of results from Gasparini *et al.* (2015) by country. For the United States the fraction of deaths attributable to temperature was 5.9 percent, of which 5.5 percent was due to cold, thus cold weather killed 14 times as many people as hot weather.

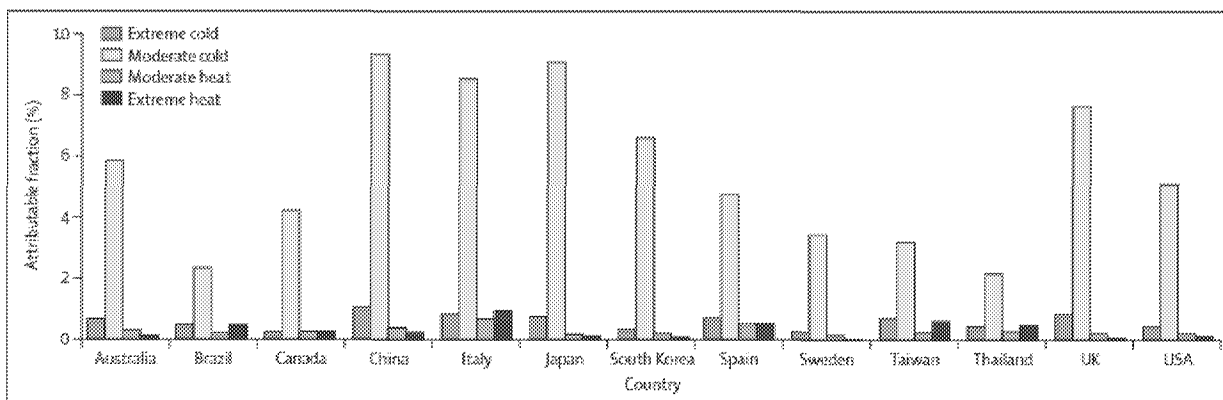


Figure 10.2. Mortality attributable to extreme and moderate cold and heat by country. Source: reproduced from Gasparini *et al.* (2015).

There is strong evidence that people adapt to weather risks. Lee and Dessler (2023) reported that 86 percent of temperature-related deaths across 40 cities in the U.S. were due to cold-related mortality, and that due to adaptation the relative risk of death declined in hot and cold cities alike as seasonal temperatures increased. Allen and Sheridan (2018) found that short, early-season cold events were 2 to 5 times deadlier than hot events, but the mortality risk of both cold and hot extremes drops to nearly zero if the events occur late in the season.

Davis *et al.* (2003) examined heat-related mortality in 28 U.S. cities from the 1960s to the end of the 1990s and found that heat-related mortality declined by three-quarters over the sample period. Bobb *et al.* (2014) examined mortality data for 106 million people in over 100 cities U.S. cities and found a 60 percent decline in average heat-related mortality over the period 1987—2005, from 51 per thousand deaths to 19. They furthermore found that the greatest drop was among seniors over the age of 75. In a study of 42 million deaths in 211 U.S. cities from 1962 to 2006, Nordio *et al.* (2015) found a more than 90 percent decline in the risk of mortality from excess heat.

In the context of large declines in heat-related mortality, rising temperatures are associated with a net saving of lives since they reduce mortality from cold events. The IPCC AR6 Working Group 2 Chapter 16.2.3.5 (O'Neill *et al.* 2022) acknowledges that heat-related mortality risk is declining over time:

Heat-attributable mortality fractions have declined over time in most countries owing to general improvements in health care systems, increasing prevalence of residential air conditioning, and behavioral changes. These factors, which determine the susceptibility of the population to heat, have predominated over the influence of temperature change.

Yet the IPCC misrepresents the overall situation in its AR6 Synthesis report. Section A.2.5 of that document states: “In all regions increases in extreme heat events have resulted in human mortality and morbidity (*very high confidence*).” But it is silent on the larger decline of deaths during extreme cold events.

The observed decline in U.S. heat-related mortality has been specifically attributed to adaptation. Wang *et al.* (2018) exploited the spatial variability of heatwave-related mortality across 209 U.S. cities from 1962 to 2006. While simple correlation appeared to imply an increase in mortality risk during heatwaves, accounting for adaptation to heatwave intensity caused the effect to fall to near zero and become statistically insignificant. They used the results of their epidemiological model to project heat-related mortality out to 2050 under four RCP warming scenarios (including RCP8.5) with and without adaptive behavior. Assuming people continue to adapt to the heatwave risks in the regions in which they live, Wang *et al.* (2018) project not only no increase in heat-related mortality, but an overall mortality *decrease* for the U.S. as a whole. They conclude that

Ignoring adaptation would result in a substantial overestimate of future mortality related to heat waves... Accounting for adaptation, the overall heat-related mortality by 2050 would not change substantially over time compared to 2006.

10.3.2 Mortality risks and energy costs

A 2016 study of U.S. long term mortality risks associated with temperature variations (Barreca *et al.* 2016) showed that increases in mortality across the U.S. are associated with both cold weather and hot weather. But over time, the introduction of electricity and the adoption of central heating and air conditioning (AC) dramatically reduced both risks, especially those associated with hot weather. Prior to 1960, a day above 90°F (32°C) added 2.2 percent to the average mortality risk rate, but after 1960 the same weather added only 0.3 percent to mortality risk, an 85 percent reduction. Prior to 1960 temperatures below 39°F (4°C) added about 1 percent to mortality risk but after 1960 the same weather only added about half that amount. Adaptation through conventional household improvements dramatically reduced public vulnerability to weather extremes. The entire reduction in hot weather mortality was attributable to widespread adoption of indoor AC, which depended on the availability of reliable and affordable electricity.

The corollary of this finding is that the use of heating and cooling systems depends on energy being affordable. Doremus *et al.* (2022) showed that wealthy and poor households in the U.S. adjust their energy expenditures at similar rates in response to moderate temperature swings, but not in response to extreme temperature swings. When temperatures swing to very cold levels ($< 5^{\circ}\text{C}$) energy spending in high-income households rises by 1.2 percent but in low-income households by only 0.5 percent. On very hot days ($> 30^{\circ}\text{C}$) electricity spending in high-income households rises by 0.5 percent but does not change at all in low-income households. The latter result is observed even in subsamples where all households have AC. The implication is that even with widespread adoption of home heating and cooling systems, inability to afford energy leaves low-income households exposed to weather extremes.

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11 CLIMATE CHANGE, THE ECONOMY, AND THE SOCIAL COST OF CARBON

Chapter summary

Economists have long considered climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in AR5. Mainstream climate economics has recognized that CO₂-induced warming might have some negative economic effects but they are too small to justify aggressive abatement policy and that trying to “stop” or cap global warming even at levels well above the Paris target would be worse than doing nothing. An influential study in 2012 suggested that global warming would harm growth in poor countries, but the finding has subsequently been found not to be robust. Studies that take full account of modeling uncertainties either find no evidence of a negative effect on global growth from CO₂ emissions or find poor countries as likely to benefit as rich countries.

Social Cost of Carbon (SCC) estimates are highly uncertain due to unknowns in future economic growth, socioeconomic pathways, discount rates, climate damages, and system responses. The SCC is not intrinsically informative as to the economic or societal impacts of climate change. It provides an index connecting large networks of assumptions about the climate and the economy to a dollar value. Some assumptions yield a high SCC and others yield a low or negative SCC (i.e. a social benefit of emissions). The evidence for or against the underlying assumptions needs to be established independently; the resulting SCC adds no additional information about the validity of those assumptions. Consideration of potential tipping points does not justify major revisions to SCC estimates.

11.1 Climate change and economic growth

11.1.1 Overview

It has long been noted that economies tend to do poorly in very cold and very hot regions, with the optimum somewhere in between (Nordhaus, 2006). Temperature-sensitive economic activity migrates, whenever possible, to where it is best suited, and society adapts to the local climate. Based in part on these observations, in 1992 Thomas Schelling, then President of the American Economic Association, argued

that any effects of climate change on U.S. economic activity would be small relative to the many other changes that would happen (Schelling 1992).

... Manufacturing rarely depends on climate, and where temperature and humidity used to make a difference, air conditioning has intervened. When Toyota chooses among Ohio, Alabama, and Southern California for locating an automobile assembly, geographical considerations are important, but not because of climate... Finance is little affected by climate; similarly for health care, or education, or broadcasting. Transportation can be affected, but improvements in all-weather landing and take-off in the last 30 years are greater than any differences that climate makes. If the average effect is a warming, iced waterways and snow removal may decline in importance. Construction is affected, mainly by cold, and if the average effect is in the direction of warming, construction may benefit slightly.

It is really agriculture that is affected. But even if agricultural productivity declined by a third over the next half century, the per capita GNP we might have achieved by 2050 we would achieve only in 2051. ...

I conclude that in the United States, and probably Japan, Western Europe, and other developed countries, the impact on economic output will be negligible and unlikely to be noticed.

Thirty years later virtually the identical point was made by the IPCC itself in the Fifth Assessment Report (Arent *et al.* 2014, emphasis added)

For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers. Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change.

Evidence since AR5 does not change this assessment. Mohaddes *et al.* (2023) found that warm weather shocks have small negative effects on U.S. state-level output but not income, while cold weather shocks negatively affect both and the impacts are about four times larger, implying a shift to warmer conditions would, if anything, yield a net economic benefit for the U.S.

These statements are validated by experience. Since 1900, the average global surface temperature anomaly warmed 1.3°C, about as much as the IPCC predicts will occur in the next century under a moderate emissions scenario. But even as the globe warmed and the population quintupled, humanity prospered as never before. For example, global average lifespan went from thirty-two years to seventy-two years, economic activity per capita grew by a factor of seven, and the death rate from extreme weather events plummeted by a factor of fifty.

While extreme weather events are costly, in all modern economies they are becoming steadily less and less important (Formetta and Feyen, 2019). Since 1990 weather-related disaster losses have declined as a proportion of global GDP (Pielke Jr, 2018, 2020) as have mortality risks (Formetta and Feyen, 2019). While economic weather-related insurance payouts are rising, this is fully explained by the growth in the size of the economy and the value of the insured asset stock. Past increases in episodes extreme weather have not had a significant effect (positive or negative) on the market value of insurance firms (Hu and McKittrick, 2015). Nor have past extreme weather events had a significant effect on U.S. banks' performance (Blickle *et al.*, 2021); warming has even been shown to be beneficial for the finance and

insurance sector (Mohaddes *et al.* 2023). Figure 11.1 below is illustrative. For these reasons, economists have long been reluctant to endorse attempts to “stop” climate change or even aggressively reduce GHG emissions because the costs would not be worth it. As one critic of the economics of climate policy put it (Storm 2017):

Mainstream climate economics takes global warming seriously, but perplexingly concludes that the optimal economic policy is to almost do nothing about it... The contrast is striking. While climate science is sending out loud-and-clear messages that fossil-fuel disinvestment must start now, letting go of coal and oil and diverting resources into renewable energy technology systems, to keep warming below the 2°C limit (IPCC 2014), mainstream climate economics claims that overly ambitious climate targets will unnecessarily hurt the economy and immediate de-carbonization is too expensive. Most climate economists thus recommend humanity to just wait-and-see.

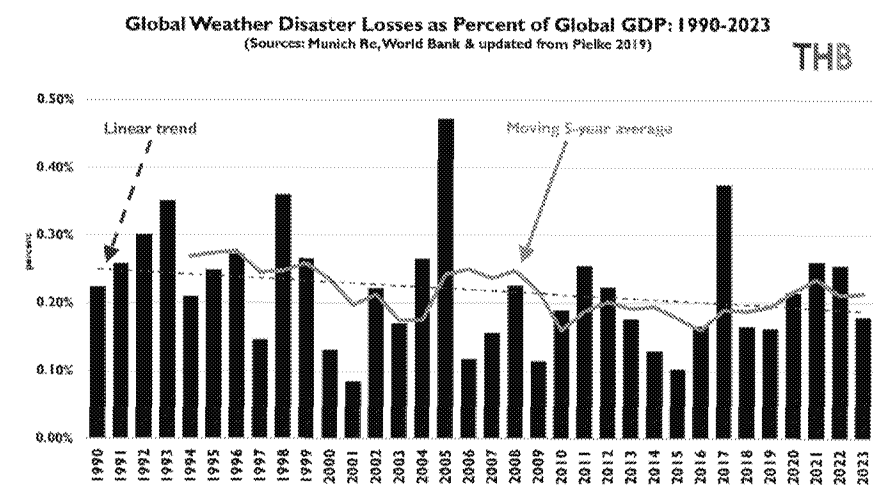


Figure 11.1 Global weather losses as a fraction of GDP. Source: Pielke Jr. (2023)

The mainstream economics position on the climate policy question is best represented by the findings over the past three decades from Integrated Assessment Models (IAMs) of climate change policy, for which Yale economist William Nordhaus was awarded the 2018 Nobel Memorial Prize in economics. IAMs combine economic, climate, and social data into a unified framework for simulating climate damages and evaluating the optimal policy response (Resources for the Future, 2025). Nordhaus’ work has generally supported modest global climate policy, with aggressive measures largely deferred to later in the century. Nordhaus developed the so-called Dynamic Integrated Model of the Climate and Economy model, or DICE, in the early 1990s (Nordhaus, 1993) to study the interaction between climate change, climate policy, and global economic growth over long times. DICE assumes global emission control can be coordinated at no cost and asks what the optimal policy target should be. The climate component of the DICE model is based on simplified climatological modeling. The version of DICE at the time of Nordhaus’ Nobel Prize award was described in Nordhaus (2018); it had a climate sensitivity parameter of 3.1°C for CO₂ doubling, consistent with the best estimate in IPCC reports (3.0°C).

The baseline (no policy) scenario incurs only \$0.4T in global abatement costs and leads to \$134.2T (trillion dollars) in global climate damages for a total cost of \$134.6T. The climate model component of

DICE projects 4.1°C warming by 2100 relative to preindustrial temperatures. Note that this is a higher estimate of warming than many IPCC climate models.

The Optimal Policy scenario barely deviates from the business-as-usual path. It aims for +3.5°C warming, in other words we modestly scale back fossil fuel use and otherwise just live with almost all the warming. This suggests that most CO₂ emissions are less harmful than the policies that would be necessary to abate them. Trying to prevent warming causes costs quickly to outstrip the benefits. Pursuing a goal of capping warming at 2.5°C creates total costs of \$177.8T, which is \$43.2T worse than doing nothing at all. Nordhaus didn't evaluate trying to reach a Paris-type target of 1.5°C warming but it would be even more costly.

A subsequent edition of DICE includes higher assumed damages from warming which, not surprisingly leads to more aggressive policy recommendations, as explained in the section below on the Social Cost of Carbon.

11.1.2 Empirical analysis of climate change and economic growth

Many other studies have used econometric methods applied to historical data, instead of IAMs, to study the potential impact of climate change on economic growth. Dell *et al.* (2012, herein DJO12) was an influential study that used a multi-country panel of national-level data spanning 1950 to 2005, in which they matched climate and economic data by averaging temperature from the local grid cell level up to the national level using population weights. They found that warming yields an insignificant positive effect on income growth in rich countries but a significant negative effect in poor countries. Moore and Diaz (2015) modified the DICE model to take that finding into account and concluded that it implied a dramatically higher Social Cost of Carbon due to the compounding effects of income loss over time.

A large subsequent literature has debated the robustness of the DJO12 findings. Burke *et al.* (2015) analyzed a global panel with temperatures averaged up to the national level and found a negative effect on growth from warming in rich and poor countries alike when the national average temperature is above 13°C. Zhao *et al.* (2018) used the G-Econ data set of Nordhaus (2006), which breaks economic activity down to the grid cell level, replicated DJO12-type results on the same subset of countries as used in DJO12 but then showed that on the full global sample warming increases growth in rich countries and poor countries alike, though the positive effect in the latter group is confined to where local temperatures are below about 16°C. Greßer *et al.* (2021) developed a regional economic data set for 1,542 sub-national regions around the world between 2005 and 2015 and found temperature had no effect on growth. Yang *et al.* (2023) updated the DJO12 data set and applied an estimator robust to mixed sample frequencies, finding that while temperature shocks exerted a temporary effect on income levels, they did not have a significant lasting effect on growth rates.

Newell *et al.* (2021) noted that there is no underlying theory to guide econometric model specification in this literature. Taking into account the arbitrary choices of which explanatory variables to include they identified over 800 possible model specifications. Using the Burke *et al.* (2015) data they used an estimation method that accounts for model uncertainty and found that the model form preferred by Burke *et al.* (2015), which implied negative effects of warming on growth even in rich countries, is explicitly excluded by the optimal model selection algorithm. Overall they could not detect a temperature effect on GDP or GDP growth, and they estimated the 95 percent confidence interval for the impact on global growth as of 2100 even under the exaggerated RCP8.5 warming scenario spans –86 percent to +388 percent. In other words the net effect is likely positive but too uncertain to distinguish from zero.

Barker (2023) criticized the DJO12 assumption that countries can be grouped into fixed “poor” and “rich” categories based on their incomes many decades ago. He noted that many countries were once poor but became rich over time, and if this is considered the original temperature effects reported by Dell *et al.* became small and insignificant.

Berg *et al.* (2023) argued that countries shouldn’t be grouped into large Rich/Poor categories because they are too heterogeneous. They instead estimated country-specific temperature response coefficients then grouped countries with similar response coefficients into small panels. They separately estimated responses to global and idiosyncratic local temperature shocks to better identify the climate signal in weather data. Overall, they found countries experiencing negative effects of warming on growth outnumbered those experiencing positive effects, but only temporarily: eventually the effects reverse such that about twice as many countries experience a net positive growth effect. They also found global (as opposed to local) temperature changes are much more likely to benefit growth in poor countries than rich ones. In a simulation to 2100, even using the extreme RCP8.5 scenario, they computed the average global GDP loss would be only 1.9 percent compared to a scenario with no warming. That is, instead of the economy growing 400 percent it would grow 392%. The implication of Nordhaus’ earlier analysis is that trying to prevent the warming would lead to far less than 392 percent growth.

To summarize, economists consider climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in the Fifth Assessment Report. Mainstream climate economics has recognized that CO₂-induced warming might have some negative economic effects but they are too small to justify aggressive abatement policy, and trying to “stop” or cap global warming even at levels well above the Paris target would be worse than doing nothing. An influential study in 2012 suggested that global warming would harm growth in poor countries but the finding has subsequently been found not to be robust (Tol 2024). Studies that take full account of modeling uncertainties either find no evidence of a negative effect on global growth from CO₂ emissions or find poor countries as likely to benefit from it as rich countries.

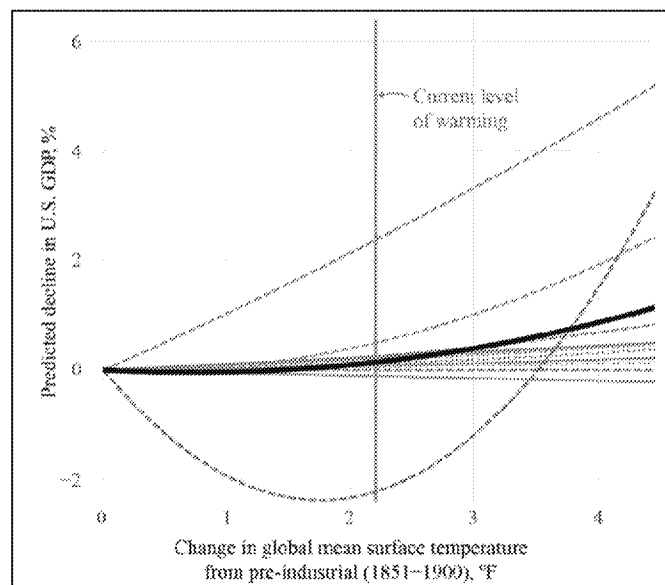


Figure 11.2: Decline in U.S. GDP per degree of warming. Source: CEA-OMB (2023)

The expectation that significant global warming would have a small impact on the U.S. economy was acknowledged quietly by the Biden Administration, even as the President was proclaiming a climate emergency. Figure 11.2, from a 2023 CEA-OMB report, shows the expected decrement in U.S. GDP as a

function of temperature rise. The colored lines show the results of a dozen peer-reviewed published studies while the solid black line is their average. The figure could be summarized as “a few percent impact for a few degrees of warming”. Given that the economy’s annual growth rate is expected to be 1-2 percent, the impact of a warming globe on the U.S. GDP is indeed negligible.

11.2 Models of the Social Cost of Carbon

The Social Cost of Carbon (SCC) is a tool for quantifying the economic impact of carbon dioxide emissions, helping policymakers weigh the costs and benefits of climate policies. It estimates the damage caused by emitting one additional ton of CO₂, expressed in dollars. More formally, the SCC is the discounted present value of the current and future marginal loss of economic welfare due to an additional ton of CO₂ entering the atmosphere.

11.2.1 *Estimating the SCC*

Although the literature refers to “estimates” of the SCC, it is not estimated in the way other economic statistics are estimated. For instance, data on market transactions including prices and quantities can be used to estimate the current inflation rate or the growth rate of per capita real Gross Domestic Product, and there are well-understood uncertainties associated with these quantities. But there are no market data available to measure many, if not most, of the marginal damages or benefits believed to be associated with CO₂ emissions, so these need to be imputed using economic models.

For example, an influential component of some SCC calculations is the perceived social cost associated with a changed risk of future mortality due to extreme weather. There is no market in which people can directly attach a price to that risk. At best economists can try to infer such values by looking at transactions in related markets such as real estate or insurance, but isolating the component of price changes attributable to atmospheric CO₂ levels is very difficult.

Economists use IAMs to compute the SCC. Two of the best known are the Climate Framework for Uncertainty, Negotiation and Distribution (“FUND”, Tol 1997) and Nordhaus’ DICE. IAMs embed a “damage function” or set of functions relating ambient temperature to local economic conditions. The assumptions embedded in the damage function will largely determine the resulting SCC. IAMs also assume a long-term discount rate or, as in DICE, compute the optimal internal discount rate as part of the solution.

One approach to developing a damage function is to begin with estimates of the costs (or benefits) of warming in specific sectors in countries around the world and aggregate up to a global amount. This was the approach used in FUND. An alternative approach is to develop a simple equation that penalizes global income according to a simple quadratic function of the average global temperature. This approach was used in DICE. In the case of the FUND model many hundreds of parameters had to be selected, whereas in DICE only three were needed and were originally chosen to assign a predetermined penalty (1.2%) to global output as of 3°C warming, with a quadratic term implying that damages grow with the square of the global average temperature anomaly. Barrage and Nordhaus (2024) recently changed the parameters to increase the penalty at 3°C to 1.6%, and added a discrete additional 1.0 percent GDP penalty at 3°C warming to account for “tipping points” (discrete large-scale environmental changes triggered by crossing a warming threshold) and a “judgmental adjustment” of 0.5 percent for excluded impacts at 3°C warming. Not surprisingly the newer version of DICE generates much higher SCC estimates than before.

The concepts of estimation and uncertainty do not readily apply to SCC calculations. By comparison, the question of whether precipitation has trended up or down along the South Carolina coast for the past

hundred years can be addressed by collecting rainfall data, estimating a trend parameter and calculating statistical confidence intervals using methods with well-understood mathematical properties. In this way uncertainty can, in principle, be resolved by collecting more data and applying more accurate methods. But no amount of data collection can change the fact that many components of the SCC are unknown and rely on judgment and opinion based on knowledge of the underlying literature on the physical effects of climate change.

SCC calculations are thus best thought of as “if-then” statements: *if* the following assumptions hold, *then* the SCC is \$X per tonne. The list of ‘if’ statements includes the premise that the world’s climate and economy work according to the representation in the IAM. One way this might fail to hold is in the timing of warming. Every IAM assumes a value of the Equilibrium Climate Sensitivity (ECS), which controls the amount of warming that results from CO₂ emissions and can be freely varied for the purpose of generating a distribution of SCC values associated with uncertainties over ECS. But as Roe and Baumann (2013) pointed out, time-to-equilibrium increases with the square of ECS, so an upward adjustment of the ECS parameter without an appropriate slowing down of the adjustment process can yield distorted present value damage estimates. In particular, the upper tail of warming associated with some commonly-used ECS distributions is physically impossible for even a thousand years into the future (Roe and Baumann 2013) yet in an IAM would be realized within a couple of centuries. Failure to align ECS with time-to-equilibrium will lead to an overestimate of the SCC value.

11.2.2 Variations in the SCC

Every level of the IAM calculation includes assumptions, some more influential than others. Key assumptions include the following.

- The discount rate: Climate damages accrue over a long time horizon and costs a century or two in the future need to be discounted to the present. The higher the discount rate the smaller the present value of future damages and vice versa. The discount rate represents the opportunity cost of spending money today rather than investing it and then having more to spend tomorrow. Some economists have argued for the use of very low discount rates in SCC calculations, resulting in policy recommendations that favor relatively large immediate investments in CO₂ emission reductions. The downside is that other investments could potentially earn a larger rate of return for society.
- Equilibrium Climate Sensitivity: IAMs have customarily employed a value of 3.0°C or 3.1°C following the IPCC’s guidance. The most recent data-driven ECS values tend to be lower than this (see Chapter 4). Dayaratna *et al.* (2017, 2020, 2023) have shown that use of lower empirically-derived ECS values dramatically lower the resulting SCC estimate, even when low discount rates are used.
- Damage function coefficients: IAMs assume CO₂ and warming cause net harms that increase exponentially with temperature. More recently, IAMs have also incorporated effects from assumed potential climate tipping points. The FUND model took limited but explicit account of CO₂ fertilization effects in agriculture. Since the coefficients were selected prior the publication of the current evidence of global greening and the magnitude of benefits to crops from elevated CO₂ (see Chapters 2 and 9) the growth effects are likely understated. The DICE model (and others) did not explicitly include any CO₂ fertilization benefit, except to the extent it was taken into account in the literature consulted when picking the damage function coefficients. The damage function in FUND contains a region in which low warming yields net benefits in many regions, a finding which is supported by econometric models of warming and growth (Berg *et al.* 2023) and econometric simulations of agricultural changes (McKittrick 2025). The DICE damage function, by construction, rules out net benefits at any warming level.

- Emission scenarios: IAMs generate SCC estimates that increase as the pre-existing concentration of CO₂ increases. Consequently the value of damages later in the century will be higher, depending on the assumed baseline emissions over the coming decades.
- Abatement costs: IAMs represent the cost to the economy of reducing CO₂ emissions. If CO₂ emission reductions are assumed to be inexpensive, then the model will conclude that the optimal policy should aim for deeper emission cuts and vice versa.

It is informative to ascertain whether SCC results are invariant to changes in some assumptions. But when different assumptions result in higher or lower SCC values, the change in the SCC value does not provide *prima facie* evidence about the validity of the assumptions. For example, in 2023 the U.S. Environmental Protection Agency raised its preferred SCC value about 5-fold over the estimates it had issued ten years earlier. This is not because new data had been collected or better mathematical methods had been invented, but because new assumptions had been used, and the validity of those assumptions was a separate question. One was that global agricultural damages were far higher than previously assumed, based on an analysis in Moore *et al.* (2017). But as discussed in Chapter 9, McKittrick (2025) showed that Moore *et al.* (2017) had used a database in which half the CO₂ change observations were missing. When as many of those observations as possible were recovered from underlying sources and the analysis was rerun, the projected crop yield losses disappeared and turned into gains at all warming levels. Hence the portion of the EPA’s SCC revision attributable to agricultural yield losses was unwarranted.

11.2.3 Evidence for low SCC

Chapter 2 reviewed evidence on climate change and greening, and Chapter 9 looked at climate change and U.S. agriculture. Evidence shows that CO₂ fertilization has a stronger beneficial effect on agriculture than was known at the time that IAMs like DICE and FUND were parameterized. Haverd *et al.* (2020) found the observed CO₂ fertilization rate has been almost double what had been predicted by crop models. Dayaratna *et al.* (2023) used the updated empirical ECS distribution estimate of Lewis (2022), which assimilates modern instrumental and paleoclimatic temperature records, and allowed for a 30 percent gain in the CO₂ fertilization benefit in the FUND model, and found that, even at a low discount rate of 2.5 percent, the median SCC as of 2050 is only \$18.67, with a 24 percent probability of the true value being negative. At a five percent discount rate the median SCC value is negative until the mid-2040s and at 2050 was only \$0.37 with a 49 percent probability of being negative. Thus, under reasonable assumptions a mainstream IAM using updated scientific inputs yields evidence consistent with the SCC not being significantly greater than zero.

It should also be noted that the SCC is focused on the social costs of CO₂ emissions from fossil fuel use. It does not measure the private marginal benefits to consumers and society from the availability of fossil fuels. Public willingness to pay for fuels of all types indicates the value to society of reliable, abundant fossil energy. Tol (2017) estimates that the private benefit of carbon is large relative to the social cost. This can be illustrated by noting that the price of a gallon of gas indicates the marginal value to the consumer of the fuel. Suppose we assume a relatively high Social Cost of Carbon of, say, \$75 per tonne. Deflated by a MCPF⁴ value of 1.5 that would result in a carbon tax of \$50 per tonne, which equates to about 44 cents per gallon of gas (Lavelle, 2019). A pre-tax price of \$3.00 per gallon would imply the marginal social benefit of the fuel is nearly seven times the marginal social cost.

11.2.4 Tipping points

SCC calculations typically consider gradual impacts of a warming climate, such as slowly-melting glaciers and increasing average temperature. A driver of potentially high values of the Social Cost of Carbon

⁴ Marginal Cost of Public Funds: the optimal carbon tax rate is the SCC divided by the MCPF (Sandmo 1977).

(SCC) is the introduction into models of discrete catastrophic outcomes associated with abrupt changes (Dietz *et al.*, 2021). They are often referred to as “tipping points.”

The term “tipping point” mingles two different physical concepts that pose different research challenges. Many physical systems are inherently stable unless acted upon with sufficient external energy. For example, an ice cap might remain intact over a wide range of temperatures but once the temperature crosses the 0°C threshold it melts. Such discontinuities are ubiquitous in nature and require an external force. Whether the force needs to be large relative to the size of the system depends on the underlying stability of the system.

A different type of tipping point is called a *bifurcation* and arises from the study of the internal dynamics of nonlinear systems (Crawford, 1991). Many systems have been observed to have more than one equilibrium point and can move between them with minimal or no external influence. For example, a weather system might have two different equilibrium states: one calm and one with a tornado. A transition from one to another can happen either with no external force or with a minuscule change, such as a flap of the proverbial butterfly’s wings (Shen *et al.* 2014). The term “tipping point” is sometimes used to mean a bifurcation of this type and implies instability inherent in the system itself, which is not necessarily dependent on outside forces. It depends, instead, on parameters of the system taking values that support the emergence of bifurcations (Crawford, 1991).

The two different concepts imply different research questions. Regarding the first we are interested in whether components of the climate system are susceptible to abrupt discontinuities in response to sufficiently-large anthropogenic forcing. Regarding the second we are interested in whether the Earth’s climate system has inherent bifurcations that imply the possibility of abrupt transitions with or without external forcing.

Models have been developed that imply the second type is a possibility. Kypke *et al.* (2020) presented a simple climate model in which the GHG concentration is one of the parameters that controls the emergence of bifurcations of the Arctic climate to one with both cold and warm equilibria. If sufficiently high GHG forcing combined with a sufficiently high rate of ocean heat transport are imposed a bifurcation becomes possible. More generally GCMs have been observed to contain bifurcations and multiple equilibria (Brunetti and Ragon, 2023).

The possible existence of bifurcations in the Earth’s climate system implies abrupt transitions are possible, not just in response to large forcing but also to small perturbations. This places tipping points into the category of low-likelihood and potentially catastrophic events, such as large meteor strikes. A key question to ask is whether those kinds of tipping points can be predicted. Current research has not resolved that question (Dakos *et al.*, 2024) and indeed might not be able to since one implication of the “butterfly effect” is the existence of predictability boundaries of nonlinear systems (Palmer *et al.*, 2014). It is therefore not obvious how to incorporate such possibilities into SCC calculations. Small variations in assumptions will lead to arbitrarily large variations in the resulting SCC with no grounds for choosing among them. If such tipping points are possible the most appropriate stance for economic policy is to maximize resilience to any form of external catastrophe since it is unlikely we could predict it or prevent it from happening.

AR6 (WGI, Chapter 1) focuses mainly on the first type of tipping point, namely an abrupt change in response to external forcing. This is also the meaning associated with popular usage of the “tipping point” concept in discussions of climate change (see [[HYPERLINK "https://report-2023.global-tipping-points.org/what-is-a-tipping-point/"](https://report-2023.global-tipping-points.org/what-is-a-tipping-point/)] for example). As summarized by AR6, there is evidence of abrupt change in the paleoclimate record, and some of these events have been interpreted as tipping points. Some projections with Earth System Models for example have produced tipping points such as Amazon forest dieback in response to specified values of CO₂ concentration or temperature increases.

The alarm surrounding climate tipping points is reflected by *The Global Tipping Points Report* that was launched at the COP28 on 6 December 2023 (Lenton *et al.*, 2023). It identifies more than 25 parts of the

climate system said to constitute tipping points. What gets classified as a climate “tipping point” is a moving target. The most common examples in the literature and assessment reports include: Greenland ice sheet disintegration, West Antarctic ice sheet disintegration, summertime disappearance of Arctic sea ice, Amazon rainforest dieback, coral reef dieoff, thawing of permafrost and methane hydrates, Atlantic Meridional Overturning Circulation collapse, boreal forest shift, West African monsoon shift, and Indian Monsoon shift.

All such tipping points require a certain amount of system instability in order to exhibit an abrupt transition in response to warming. For this reason there seems to be very little to discriminate between a tipping event and natural climate variability. Natural climate variability has in the past produced shifts in the West African and Indian monsoons, Amazon forest and coral reef dieback, and disintegration of parts of the Greenland and West Antarctic ice sheets. These impacts can reverse on the decadal and century timescales associated with natural climate variability and ecosystem responses.

Some abrupt changes are potentially more consequential, including collapse of the West Antarctic ice sheet and collapse of the Atlantic Meridional Overturning Circulation (AMOC). AR6 WG1 Summary for Policy Makers states:

The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all emission scenarios. While there is *high confidence* in the 21st century decline, there is only *low confidence* in the magnitude of the trend. There is *medium confidence* that there will not be an abrupt collapse before 2100. (C.3.4)

There is limited evidence for low-likelihood, high-impact outcomes (resulting from ice-sheet instability processes characterized by deep uncertainty and in some cases involving tipping points) that would strongly increase ice loss from the Antarctic Ice Sheet for centuries under high GHG emissions scenarios (e.g., SSP5-8.5). (B.5.2)

For the purpose of SCC calculations, the research question implied by this type of tipping point is whether such events have been observed in the past in climate conditions similar to what we currently experience or will in the near future. AR6 finds little evidence for impending collapse of the Atlantic Meridional Overturning Circulation or the West Antarctic ice sheet. It finds there is no tipping point associated with Arctic Sea ice (AR6 Technical Summary p. 76)

Dietz *et al.* incorporated several potential tipping points (abrupt changes) into an SCC model and found they added about 25 percent to the estimate, mainly associated with thawing permafrost and release of methane hydrates. However, the IPCC considers this scenario *very unlikely* (AR6 Technical Summary p. 107).

In summary, there might be unknown bifurcation tipping points that are associated with natural climate processes, but this possibility does not translate into specific guidance on the SCC. There are potential abrupt change points in the climate system in response to warming, although the IPCC assigns low probabilities to most, including the largest ones. When these have been considered, the result is only a modest increase in the SCC value in the 21st century.

11.2.5 Are there alternatives?

It is increasingly being argued that the SCC is too variable to be useful for policymakers. Cambridge Econometrics (Thoung, 2017) stated it’s “time to kill it” due to uncertainties. The UK and EU no longer use SCC for policy appraisal, opting for “target-consistent” carbon pricing (UK Department for Energy Security and Net Zero 2022, Dunne 2017). However, the uncertainty of SCC estimates doesn’t mean that other regulatory measures are inherently better or more efficient. Many emissions regulations (such as

electric vehicle mandates, renewable energy mandates, energy efficiency regulations and bans on certain types of home appliances) cost far more per tonne of abatement than any mainstream SCC estimate, which is sufficient to establish that they fail a cost-benefit test.

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12 GLOBAL CLIMATE IMPACTS OF U.S. EMISSIONS POLICIES

Chapter Summary

U.S. policy actions are expected to have undetectably small direct impacts on the global climate and any effects will emerge only with long delays.

12.1 The scale problem

The emissions rates and atmospheric concentrations of criteria air contaminants are closely connected because their lifetimes are short and their concentrations are small; when local emissions are reduced the local pollution concentration drops rapidly, usually within a few days. But the global average CO₂ concentration behaves very differently, since emissions mix globally and the global carbon cycle is vast and slow. Any change in local CO₂ emissions today will have only a very small global effect, and only with a long delay.

Following the emission of a pulse (release) of CO₂ into the atmosphere only about 40±15 percent of the extra CO₂ will have been sequestered after twenty years. That fraction rises to 75±10 percent after a thousand years, and the remainder will be gradually removed over the ensuing tens of thousands of years (Ciais *et al.*, 2013, pp. 472-473). Consequently, any reduction in U.S. emissions would only modestly slow, but not prevent, the rise of global CO₂ concentration. And even if global emissions were to stop tomorrow, it would take decades or centuries to see a meaningful reduction in the global CO₂ concentration and hence human influences on the climate.

Reducing the atmospheric stock of CO₂ would require emissions to fall below the natural sequestration rate, assuming the entire increase is anthropogenic. Since that rate has been averaging about 50 percent of emissions in recent decades, a reduction of global emissions by 50 percent would (at least temporarily) halt the rise in atmospheric CO₂. The 1997 Kyoto Protocol proposed to cap industrial nations' CO₂ emissions at a modest five percent below 1990 levels by the year 2012. Even though this policy was too difficult for most nations to implement, full compliance would not have substantially reduced atmospheric CO₂ levels. It would only have slightly slowed CO₂ growth, reaching the projected year 2100 level in 2105 instead (Wigley, 1998). Lomborg (2016) estimated that full compliance with the Paris Accord would not stop warming, it would only prevent about 0.1C warming and delay hitting the baseline year 2100 temperature levels by about a decade.

Thus, in contrast with conventional air pollution control, even drastic local actions will have negligible local effects, and only with a long delay. The practice of referring to unilateral U.S. reductions as “combatting climate change” or “taking action on climate” therefore reflects a profound misunderstanding of the scale of the issue.

12.2 Case study: U.S. motor vehicle emissions

The scale problem can be illustrated with reference to U.S. motor vehicles. The EPA's 2009 Endangerment Finding focused on CO₂ emissions from cars and light-duty trucks in the U.S. because Section 202(a) of Clean Air Act mandates the EPA to set emissions standards for motor vehicles if pollutants are found to endanger public health or welfare. The 2009 Endangerment Finding therefore obligated the EPA to regulate emissions from new motor vehicles, ostensibly to reduce or eliminate climate-related harms to the U.S. public.

Two questions that naturally arise are: (1) How large a reduction in CO₂ emissions would result from such regulation? and (2) What would be the climate impact of such regulation?

The first question can be addressed by comparing U.S. vehicle-based CO₂ emissions to the global total. The second question can be addressed by using the fact that the reduction in global warming would be, according to the models relied upon by the EPA, proportional to the reduction in global emissions, keeping in mind that the change in the CO₂ content of the atmosphere in any given year is the result of total global CO₂ emissions, not just U.S. emissions.

In 2022, the emissions from U.S. cars and light duty trucks totaled 1.05 billion metric tons of carbon dioxide (GtCO₂, EPA 2024). Meanwhile global CO₂ emissions from energy use totaled 34.6 GtCO₂ (Energy Institute 2024). Hence U.S. cars and light trucks account for only 3.0 percent of global energy-related CO₂ emissions. To a first approximation we can say that even eliminating *all* U.S. vehicle-based emissions would retard the accumulation of CO₂ in the atmosphere by a year or two over a century.

It would also reduce the overall warming trend by at most about 3 percent. For the period 1979-2023, which has the most extensive global coverage of a variety of weather data types, warming trends are determined to a precision of about ± 15 percent, so the impact of reducing the rate of global warming by eliminating U.S. vehicle CO₂ emissions would be far below the limits of measurability. Given that global-average temperature is the most direct climate change metric, impacts on any secondary climate metrics (e.g. severe weather, floods, drought, etc.) from reducing U.S. vehicle CO₂ emissions would be even less measurable.

Consequently, in contrast to the case of local air contaminants like particulates and ozone, even the most aggressive regulatory actions on GHG emissions from U.S. vehicles cannot be expected to remediate alleged climate dangers to the U.S. public on any measurable scale.

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GLOSSARY

2XCO₂: Doubling of the atmospheric carbon dioxide (CO₂), a commonly used baseline for addressing climate change. In 2025, atmospheric CO₂ concentrations were approximately 50 percent of the way to 2XCO₂ compared to 1800.

ABATEMENT: In the context of environmental policy, the reduction of emissions.

ACE (Accumulated Cyclone Energy): A statistical measure of a tropical cyclone's energy accumulated over its lifetime, calculated from a summation of the square of maximum sustained wind speeds.

ACIDIFICATION: A commonly used term for the reduction in ocean pH from more alkaline to less alkaline values.

ACRIM (Active Cavity Radiometer Irradiance Monitor) GAP: the gap in total solar irradiance data between 1989 and 1991 caused by a delay in the launch of a satellite-borne monitor in time to overlap and intercalibrate with the prior system.

AEROSOLS: Tiny solid or liquid particles suspended in the air.

ALKALINE: Having a chemical pH greater than 7.0. The “opposite” of acidic, which means a pH less than 7.0.

AMBIENT: Relating to the immediate surroundings of something.

AMO: Atlantic Multidecadal Oscillation, a 60-year cycle of sea surface temperatures in the North Atlantic.

ANTHROPOGENIC: Created by humans.

AR (Assessment Reports): Periodic assessments published by the Intergovernmental Panel on Climate Change evaluating current knowledge of the climate system, global change, and associated issues. An AR now consists of reports from three working groups, the first (WG1) concerned with physical science and the others concerned with societal impacts and mitigation strategies. The most recent was AR6.

ATTRIBUTION: Assertion of a causal relation, chiefly from anthropogenic GHG emissions to observed climate patterns.

AUTOCORRELATION: The phenomenon in which the current value of a random time series variable is correlated with its value in a previous time period.

BIOMASS: The total quantity or weight of organic matter in a given area or volume.

CARBON: The 6th element in the periodic table. Popularly used as a shorthand term for carbon dioxide.

CMIP (Coupled Model Intercomparison Project): The Intergovernmental Panel on Climate Change's organized effort to compare many different global ocean-atmosphere climate models when they are all forced with the same emissions scenario(s). The two most recent were the CMIP5 and CMIP6 for, respectively, AR5 and AR6.

CLIMATE CHANGE: A change in climate due to human influences, as opposed to climate variability which is natural in origin.

CONUS: The contiguous 48 U.S. states.

DICE (Dynamic Integrated model of the Climate and Economy): An Integrated Assessment Model developed by William Nordhaus in 1993.

DISCOUNT RATE: The interest rate used to convert future costs and benefits into their present value. Varies inversely with present value so a high discount rate reduces the present value of future costs and benefits.

DRY ICE: Frozen carbon dioxide.

ECONOMETRICS: The branch of economics concerned with the use of statistical methods (chiefly multiple regression) to analyse economic systems.

ECS (Equilibrium Climate Sensitivity): The total amount of eventual global-average surface warming in response to a hypothetical doubling of the atmospheric CO₂ concentration compared to pre-Industrial levels.

EL NIÑO: The warm phase of the El Niño – Southern Oscillation, involving weaker upwelling of cold water off the South American coast and weaker Pacific trade winds.

EMISSIONS SCENARIO: An assumed scenario of future greenhouse gas emissions (or resulting atmospheric concentrations) based upon assumptions regarding global economic activity, the prevalence of fossil fuel use, and (sometimes) global carbon cycle model estimates of the rate of CO₂ uptake by land and ocean.

ENDANGERMENT FINDING (EF): The 2009 finding by the Administrator of the Environmental Protection Agency that emissions of well-mixed greenhouse gases (primarily CO₂) endanger human health and welfare.

ENSO: El Niño – Southern Oscillation, a prominent natural climate fluctuation involving year-to-year variations in the upwelling of cold water off the equatorial coast of South America and associated strengthening or weakening of trade winds across the Pacific Ocean.

FACE: (Free-Air CO₂ Enrichment) Large-scale open-air studies that expose plants to elevated CO₂ levels, simulating future climate scenarios.

FOSSIL FUEL: A natural hydrocarbon fuel such as coal, oil, or natural gas formed in the geological past from the remains of living organisms.

FUND (Framework for Uncertainty, Negotiation, and Distribution): An Integrated Assessment Model developed by Richard Tol in 1997.

GBR (Great Barrier Reef): The world's largest coral reef ecosystem located off the northeast coast of Australia.

GDP (Gross Domestic Product): Total market value of all the final goods and services produced within a country's border, usually over one year.

GHCN (Global Historical Climatology Network): A time-varying number of globally distributed weather stations making hourly, daily, or monthly measurements of precipitation, temperature and sometimes snowfall and snow depth.

GLOBAL GREENING: The satellite-observed increase in greenness in most vegetated land areas observed since the early 1980s.

GNP (Gross National Product): Total market value of all the final goods and services produced by the citizens of a country, including exports and imports, usually over one year.

GDP (Gross National Product): Total market value of all the domestically-produced final goods and services produced by the citizens of a country, usually over one year.

GREENHOUSE EFFECT (GHE): The tendency for any planetary atmosphere containing greenhouse gases to be warmer in the lowest layers than if those gases did not exist.

GREENHOUSE GAS (GHG): An atmospheric gas that absorbs and emits infrared radiation, especially water vapor, CO₂, and methane.

HURST PHENOMENON: See long term persistence.

HYDROLOGY: The study of the movement of water, especially on land and in the atmosphere.

IAM (Integrated Assessment Model): A computerized tool that combines economics, climate science, and social sciences to provide quantitative relationships between human and Earth systems, helping to inform policy decisions.

IEA (International Energy Agency): A Paris-based intergovernmental organization, established in 1974, that provides policy recommendations, analysis and data on the global energy sector.

IPCC (Intergovernmental Panel on Climate Change): A panel of international experts and governmental representatives established by the United Nations and World Meteorological Organization in 1988 to provide governments at all levels with scientific information that they can use to develop climate policies.

IR (Infrared): Heat radiation that all solid objects and greenhouse gases emit by virtue of their temperature.

LA NIÑA: The cool phase of ENSO, involving stronger upwelling of cold water off the South American coast and stronger Pacific trade winds.

LONG TERM PERSISTENCE (LTP, or HURST PHENOMENON): A form of autocorrelation in which random fluctuations induce long term but not permanent changes in the mean value of a series, which shows up in some climate data series as cyclical or trending patterns on short time scales.

MAIZE: Corn.

MODEL: A computer code or collection of codes which quantify our knowledge of various processes and the interactions between those processes.

MORTALITY: Death or number of deaths, usually expressed for a specific population and period.

NCA (National Climate Assessment): A periodic report mandated by the Global Change Research Act of 1990 summarizing the impact of climate change on the United States. There have been five NCA reports: NCA1 (2000), NCA2 (2009), NCA3 (2014), NCA4 (2017-18), and NCA5 (2023).

OECD (Organization for Economic Cooperation and Development): A group of 38 member countries that have a democratic system of government and free economic systems.

PALEOCLIMATE: Climate of the distant past, before modern weather instruments were widely used (typically pre-1850), necessitating the use of “proxy” measurements such as tree rings, ice core, pollen records, etc.

PDI (Power Dissipation Index): A statistical estimate of the accumulated destructive potential of a tropical cyclone over time, calculated as a summation of the cube of the maximum sustained wind speeds.

PDO: Pacific Decadal Oscillation, a recurring ocean-atmosphere interaction centered over the Pacific basin associated with predominantly warm or cool patterns that influence the global climate.

PHOTOSYNTHESIS: The process by which plants grow, requiring carbon dioxide, water, and light at sufficiently warm temperatures (10 to 35 deg. C for optimal function).

PPM: Parts per million, a measure of the concentration of a substance in (for example) the atmosphere

PRE-INDUSTRIAL: The near-term historical period before which human greenhouse gas emissions were considered significant, usually assumed to be the mid-1700s.

RADIATIVE FEEDBACK: A change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in surface temperature.

RADIATIVE FORCING: The change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in greenhouse gases, anthropogenic aerosols, volcanoes, etc.

RCP (Representative Concentration Pathway) SCENARIOS: Different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Fifth Assessment Report (AR5). RCP scenarios have a number label (e.g. RCP6.0) indicating how much radiative forcing they assume in 2100 relative to pre-Industrial times, in Watts per square meter. RCP4.5 and RCP6.0 are intermediate scenarios, whereas RCP8.5 is an extreme scenario with very large future emissions of greenhouse gases.

REGRESSION: A statistical method for selecting the coefficients of a linear equation to explain the behaviour of a dependent variable in terms of variations in one or more explanatory variables.

RICARDIAN ANALYSIS: A method used in environmental economics named after David Ricardo to estimate the economic impacts of climate change, particularly on agriculture, by making use of the hypothesis that expected changes in the return to future agricultural activity will be capitalized into current land values.

SCC (Social Cost of Carbon): An estimate of the net economic damages, measured in present-value dollars, caused by emitting one additional ton of CO₂ into the atmosphere.

SSP (Shared Socioeconomic Pathway) SCENARIOS: Different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Sixth Assessment Report (AR6). Some of the SSP scenarios are analogous to the older RCP scenarios, for purposes of continuity and comparison to earlier climate model assessments.

TC: Tropical cyclone.

TMAX: The daily maximum surface air temperature.

TMIN: The daily minimum surface air temperature.

TOA: Top of atmosphere.

TONNE: Metric ton.

TOXICOLOGY: The study of the adverse effects of chemical substances on living organisms.

TREND: A coefficient, usually estimated using linear regression, representing the slope of a line of best fit through a time series of data, indicating any tendency for the series mean to move up or down over time.

TSI (Total Solar Irradiance): The measure of the total amount of incident solar radiation per unit area, including all wavelengths of electromagnetic radiation, that reaches the Earth's atmosphere. Typically shown in units of watts per square meter (W/m²).

UHI (Urban Heat Island): The tendency for inhabited areas to be warmer than their rural surroundings, due to the replacement of natural land and vegetation with roads, parking lots, buildings, and waste heat sources.

USHCN: The U.S. Historical Climatology Network, consisting of quality-controlled temperature and precipitation data from 1,218 surface weather stations.

METADATA FOR FIGURES AND TABLES

Figure 2.1 Screen shot from Figure 3 of Zhu *et al.* 2016 [HYPERLINK "<https://www.nature.com/articles/nclimate3004>"]

Figure 2.2 Data replotted from Berner 2006 Figure 18, with annotation in red added by authors [HYPERLINK "<https://www.sciencedirect.com/science/article/pii/S0016703706002031>"]

Figure 2.3 Screen shot from Gerhart and Ward (2010) Figure 2 [HYPERLINK "<https://nph.onlinelibrary.wiley.com/doi/pdf/10.1111/j.1469-8137.2010.03441.x>"]

Figure 2.4 Screenshot from Copernicus Marine Services [HYPERLINK "https://data.marine.copernicus.eu/product/GLOBAL_OMI_HEALTH_carbon_ph_area_averaged/description"]

Figure 2.5 Screen shot from AIMS (2023) Figures 2-4 [HYPERLINK "https://www.aims.gov.au/sites/default/files/2022-08/AIMS_LTMP_Report_on%20GBR_coral_status_2021_2022_040822F3.pdf"]

Figure 3.1.1 Screen shot of AR6 WG1 Ch2 Fig 10

Figure 3.1.2 Screen shot of AR6 WG1 Ch7 Fig 7-6

Figure 3.1.3 Author created figure. CO2 data source: [HYPERLINK "<https://gml.noaa.gov/ccgg/trends/index.html>"]

Figure 3.2.1 Screen shot from Hausfather *et al.* (2019) Figure S4 [HYPERLINK "<https://doi.org/10.1029/2019GL085378>"]

Figure 3.2.2 Author created figure. Data source: Freidlingstein *et al.* (2024) [HYPERLINK "<https://essd.copernicus.org/preprints/essd-2024-519>"]
Data source: [HYPERLINK "<https://globalcarbonbudget.org/download/1442/>"]

Figure 3.2.3 Author-created using OLS trends, Data source: [HYPERLINK "<https://globalcarbonbudget.org/download/1442/>"]

Figure 3.2.4 Author-created using OLS trends, Data source: [HYPERLINK "<https://globalcarbonbudget.org/download/1442/>"]

Figure 4.1 Screen shot from Scafetta (2021) Figure 1 [HYPERLINK "<https://doi.org/10.3390/cli9110161>"]

Figure 5.1 Data source: [HYPERLINK "<https://climexp.knmi.nl/start.cgi>"]. Author-created figure. One ensemble member per model, yearly average temperatures are computed from the global monthly raw temperatures; ‘range’ is the warmest model temperature minus the coolest model temperature in each year; standard deviation computed across all 33 models’ raw temperatures in each year.

Figure 5.2 Screen shot from Scafetta (2023) Figure 2 [HYPERLINK "<https://doi.org/10.1007/s00382-022-06493-w>"]

Figure 5.3 Author created figure. Data source: [[HYPERLINK "https://climexp.knmi.nl/start.cgi"](https://climexp.knmi.nl/start.cgi)]. One SSP370 ensemble member per model. Linear OLS trends computed from global monthly temperature anomalies relative to 1981-2010.

Figure 5.4 Author created figure, based on Figure 3 of McKittrick and Christy (2020) [[HYPERLINK "https://doi.org/10.1029/2020EA001281"](https://doi.org/10.1029/2020EA001281)]. Updated using same methods and data extended from 2014 to 2024, see McKittrick and Christy (2025) in chapter references.

Figure 5.6 Screen shot of IPCC AR5 Figure 10.SM1, with author annotations

Figure 5.7 Author created figure following Christy and McNider (2017) [[HYPERLINK "https://doi.org/10.1007/s13143-017-0070-z"](https://doi.org/10.1007/s13143-017-0070-z)] with updated data available at [[HYPERLINK "https://www.nsstc.uah.edu/data/cmip6/ERA5_REANALYSES/"](https://www.nsstc.uah.edu/data/cmip6/ERA5_REANALYSES/)] and [[HYPERLINK "https://www.nsstc.uah.edu/data/cmip6/JRA3Q_REANALYSES/"](https://www.nsstc.uah.edu/data/cmip6/JRA3Q_REANALYSES/)] compiled here [[HYPERLINK "https://www.nsstc.uah.edu/data/cmip6/CWG25_Fig_5.7_Table_250627.xlsx"](https://www.nsstc.uah.edu/data/cmip6/CWG25_Fig_5.7_Table_250627.xlsx)]

Figure 5.8 Screen shot from [[HYPERLINK "https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhland&ui_season=1"](https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhland&ui_season=1)] (accessed May 27, 2025)

Figure 5.9 Screen shot from Rugenstein and Hakuba (2023) Figure 1 [[HYPERLINK "https://doi.org/10.1029/2022GL101802"](https://doi.org/10.1029/2022GL101802)]

Figure 5.10 Author created figure. Data source [[HYPERLINK "https://climexp.knmi.nl/start.cgi"](https://climexp.knmi.nl/start.cgi)]. OLS linear trends. One SSP370 ensemble member per model, averaged surface air temperatures for June through August over 31N to 49N latitude, 84W to 102W longitude. Observed temperature data for same months from NOAA/NCEI at <https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/statewide/time-series> for the 12 Corn Belt states averaged together.

Figure 6.1.1 Author replot of Figure 10 from Koutsoyiannis (2013) [[HYPERLINK "http://dx.doi.org/10.1080/02626667.2013.804626"](http://dx.doi.org/10.1080/02626667.2013.804626)]

Figure 6.2.1 Screen shot of figure from Maue (2025) [[HYPERLINK "https://climatlas.com/tropical/"](https://climatlas.com/tropical/)]

Figure 6.2.2 Author created figure. Data from National Hurricane Center (2024) [[HYPERLINK "https://www.nhc.noaa.gov/climo/"](https://www.nhc.noaa.gov/climo/)]

Figure 6.2.3 Author created figure. Data from NOAA HRD [[HYPERLINK "https://www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html"](https://www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html) \t "_new"]

Table 6.2.1 Author created table. Data from NOAA HRD [[HYPERLINK "https://www.aoml.noaa.gov/hrd/hurdat/most_intense.html"](https://www.aoml.noaa.gov/hrd/hurdat/most_intense.html) \t "_new"]

Figure 6.3.1 Screen shot from NCA4 Figure 6.4

Figure 6.3.2 Author created figure. Data source: [[HYPERLINK "https://www.nsstc.uah.edu/data/ushcn_jrc/"](https://www.nsstc.uah.edu/data/ushcn_jrc/)]

Figure 6.3.3 Author created figure. Data source: [[HYPERLINK "https://www.nsstc.uah.edu/data/ushcn_jrc/"](https://www.nsstc.uah.edu/data/ushcn_jrc/)]

Figure 6.3.4 Author created figure. Data source: [HYPERLINK "https://www.nsstc.uah.edu/data/ushcn_jrc/"]

Figure 6.3.5 Author created figure Data source: [HYPERLINK "https://www.nsstc.uah.edu/data/ushcn_jrc/"]

Figure 6.3.6 Author created figure. Data source: [HYPERLINK "https://www.nsstc.uah.edu/data/ushcn_jrc/"]

Figure 6.3.7 Screen shot from [HYPERLINK "https://www.globalchange.gov/indicators/heat-waves"]

Box tables. Author created table. Data from McKittrick and Christy (2025)

Figure 6.4.1 Author created figure. Data from McKittrick and Christy (2025)

Figure 6.4.2 Author created figure. Data from McKittrick and Christy (2025)

Figure 6.4.3 Author created figure. Data from McKittrick and Christy (2025)

Figure 6.4.4 Author created figure. Data from McKittrick and Christy (2025)

Figure 6.4.5 Author created figure. Data from McKittrick and Christy (2025)

Figure 6.5.1 Author created figure. Data source: [HYPERLINK "https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv"]

Figure 6.7.1 Author created figure. Data source: [HYPERLINK "https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0"] accessed June 16, 2025. OLS trend line added.

Figure 6.8.1 Screen shot from Lizundia-Loiola *et al.* (2021) Figure 12.

Figure 6.8.2 Screenshot from Marlon *et al.* (2012) Figure 2 panel C. [HYPERLINK "https://www.pnas.org/doi/pdf/10.1073/pnas.1112839109"]

Figure 6.8.3 Author created Figure. Data 1926 to 2016: [HYPERLINK "https://web.archive.org/web/20200212033452/https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html"]. Post-2017 [HYPERLINK "https://www.nifc.gov/fire-information/statistics/wildfires"] Accessed June 16, 2025.

Figure 7.1 Screenshot from [HYPERLINK "https://tidesandcurrents.noaa.gov/sltrends/"]

Table 7.1 Author created table. From Section 6.2 of [HYPERLINK "https://judithcurry.com/wp-content/uploads/2018/11/special-report-sea-level-rise-3.pdf"]

Figure 7.2 Screenshot from [HYPERLINK "https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290"] (downloaded 4/22/25)

Figure 7.3 Screenshot from

[HYPERLINK "https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8771450"]
(downloaded 4/22/2025)

Figure 7.4 Screenshot from

[HYPERLINK "https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8761724"]
(downloaded 4/22/25)

Figure 7.5 Screenshot from

[HYPERLINK "https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750"]
(downloaded 4/22/25)

Figure 7.6 Author created figure. Data from [HYPERLINK

"https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750"]

Figure 8.1 Screenshot from

[HYPERLINK "<https://crudata.uea.ac.uk/cru/data/temperature/HadCRUT5.0Analysis.pdf>"]

Figure 8.2 Screenshot from Hansen and Karecha (2025) Figure 1

[HYPERLINK "<https://www.columbia.edu/~jeh1/mailings/2025/CloudFeedback.13May2025.pdf>"]

Table 8.1 Screenshot of column 1 of Table 12.12 IPCC AR6 Working Group I report

Figure 9.1 Screenshot From Taylor and Schlenker (2021) Figure 1

[HYPERLINK "<https://www.nber.org/papers/w29320>"]

Figure 9.2 Screenshot from McKittrick (2025) Figure 1

[HYPERLINK "<https://www.nature.com/articles/s41598-025-90254-2>"]

Figure 10.1 Screenshot from Pielke (2024) [HYPERLINK "<https://www.nature.com/articles/s44304-024-00011-0>"] Figure 3.

Figure 10.2 Screenshot from Gasparini *et al.* (2015) Figure 2

[HYPERLINK "[http://dx.doi.org/10.1016/S0140-6736\(14\)62114-0](http://dx.doi.org/10.1016/S0140-6736(14)62114-0)"]

Figure 11.1 Screen shot from Pielke Jr (2023)

[HYPERLINK "<https://rogerpielkejr.substack.com/p/global-disaster-losses1990-2023>"]

Figure 11.2 Screenshot from CEA-OMB (2023) [HYPERLINK

"<https://bidenwhitehouse.archives.gov/wp-content/uploads/2023/03/CEA-OMB-White-Paper.pdf>"]
Figure 1.

ABOUT THE AUTHORS

John Christy, Ph.D. is the Distinguished Professor of Atmospheric and Earth Sciences and Alabama's State Climatologist at the University of Alabama in Huntsville. He has a B.A. (Mathematics) from CSU Fresno and an M.S. and Ph.D. (Atmospheric Sciences) from the University of Illinois in Urbana-Champaign. He is a Fellow of the American Meteorological Society and recipient of The NASA Medal for Exceptional Scientific Achievement for constructing, with Dr. Roy Spencer, the first global atmospheric temperature dataset from polar orbiting satellites. He served as Lead Author of the 3rd IPCC Assessment Report (2001), he coauthored the National Academy of Science expert report on Surface Temperature Reconstructions (2006), and he has served on the NOAA Climate Change Science Program, NASA's Earth Science Subcommittee, the National Research Council Space Studies Board and the EPA Science Advisory Board. In addition, Dr. Christy has given testimony in 20 Congressional Hearings.

Judith Curry, Ph.D. is Professor Emerita at the Georgia Institute of Technology, where she served as Chair of Earth and Atmospheric Sciences for 13 years. She is President and co-founder of Climate Forecast Applications Network (CFAN). Curry has a PhD in Geophysical Sciences from the University of Chicago. She has authored or coauthored 192 peer-reviewed papers in atmospheric and climate sciences, two textbooks, and most recently the book *Climate Uncertainty and Risk*. Curry is a Fellow of the American Meteorological Society, the American Association for the Advancement of Science, American Geophysical Union, and a Member of the American Academy of Sciences and Letters. She has served on several Science Steering Committees of the World Climate Research Program and also the DOE Biological & Environmental Research Advisory Committee, Earth Science Subcommittee of the NASA Advisory Council, and the NRC Space Studies Board and Climate Research Committee. Dr. Curry has given testimony in 13 Congressional Hearings..

The Honorable Steven E. Koonin, Ph.D. is the Edward Teller Senior Fellow at Stanford's Hoover Institution. He has served as Under Secretary for Science at the Department of Energy (2009-2011), as Chief Scientist for British Petroleum (2004-2009), and as a professor at Caltech (1975 – 2004, the last nine years as Vice President and Provost). Koonin is a member of the National Academy of Sciences and the JASON group of government advisors, as well as a Governor of Lawrence Livermore National Laboratory, having served in similar capacities for the Los Alamos, Sandia, Brookhaven, and Argonne National Laboratories. Other prior roles include a University Professor at New York University, a non-resident Senior Fellow at the American Enterprise Institute, and a Trustee of the Institute for Defense Analyses. Koonin has a BS in Physics from Caltech and a PhD in Theoretical Physics from Massachusetts Institute of Technology. He authored the 2021 bestseller *Unsettled: What Climate Science Tells Us, What It Doesn't, and Why It Matters*, the 1985 textbook *Computational Physics*, and some 200 peer-reviewed papers in physics and astrophysics, scientific computation, energy technology and policy, and climate science.

Ross McKittrick, Ph.D., is a Professor of Environmental Economics at the University of Guelph in Ontario, Canada. He holds a BA in economics from Queen's University, and an MA and Ph.D. in economics from the University of British Columbia. He has published widely in both economics and physical science journals on topics related to climate change, pollution and public policy. His book *Economic Analysis of Environmental Policy* was published by the University of Toronto Press in 2010. His background in applied statistics has led him to author or coauthor peer-reviewed publications across a wide range of topics in the physical sciences including paleoclimate reconstruction, malaria transmission, surface temperature measurement, climate attribution methodology and climate model evaluation. Professor McKittrick has made many invited academic presentations around the world, was an invited contributor to the 2006

National Academy of Sciences report on Surface Temperature Reconstructions, has served as an expert reviewer for the last three IPCC Assessment Reports (Working Groups I and II) and has testified before the U.S. Congress and committees of the Canadian House of Commons and Senate.

Roy W. Spencer, Ph.D., is a Principal Research Scientist at the University of Alabama in Huntsville. He holds a BS in Atmospheric and Oceanic Science from the University of Michigan, and MS and PhD in Meteorology from the University of Wisconsin -Madison. Spencer's published research has focused on monitoring of weather processes and climate change from Earth-orbiting satellites, as well as using simple physical models for diagnosing climate sensitivity and climate feedbacks. As a NASA Senior Scientist for Climate Studies he served as the U.S. Science Team Leader for the Advanced Microwave Scanning Radiometer (AMSR-E) flying on the Aqua satellite, providing our most accurate global measurements of sea surface temperatures, sea ice, and several other features of the climate system. Along with Dr. John Christy, Spencer developed the first satellite-based technique for global temperature monitoring, for which they received NASA's Exceptional Scientific Achievement Medal and the American Meteorological Society's Special Award.

From: Google Calendar <calendar-notification@google.com>
Sent: Friday, August 1, 2025 2:30 PM
Cc: John Christy
Subject: Notification: [EXTERNAL] DOE reviews @ Fri Aug 1, 2025 2pm - 2:30pm (CDT) (John Christy)

You have an upcoming event

[EXTERNAL] DOE reviews

Friday Aug 1, 2025 · 2pm – 2:30pm (Central Time - Chicago)

Attachments

image001.png

image002.jpg

Hi all,

Let's see who can join a quick MS Teams meeting at 3pm ET today. The main agenda item is to ensure continuity once I go back to Cato, which happens later today. I'll still be reachable on my personal email and phone, but I'll lose access to DOE equipment, email, etc.

I'd also like to hear everyone's thoughts on 1) possibly expanding the CWG to include scientists of your and the Secretary's choosing, and 2) the best way to engage expert peer reviewers outside of the DOE enterprise (can't include national lab employees this time).

Looking forward to touching base with everyone!

Best,
Travis

Microsoft Teams Need help?
Join the meeting now
Meeting ID: 290 077 410 479 1
Passcode: B63Po7tt

Dial in by phone
+1 443-457-0649,,530567526# United States, Brooklyn Park
Find a local number

Phone conference ID: 530 567 526#
For organizers: Meeting options | Reset dial-in PIN

From: Judith Curry >
Sent: Thursday, July 31, 2025 7:29 PM
To: Ross McKittrick >
Cc: Fisher, Travis >; Roy Spencer >; Park, Charles >; John Christy >; Steven Koonin >; Loucks, Joshua >; Cohen, Seth >
Subject: Re: [EXTERNAL] DOE reviews

got it i'll start working on it. THANKS

On Thu, Jul 31, 2025 at 2:57 PM Ross McKittrick > wrote:
Judy, here is a zipped folder with the review comment digest files. #1 has multicolored comments so will take a bit of editing to compile into single responses. #2 there are 2 files I think mine [RM] has the later aggregation but check both. #3-#8 have responses in green that we talked through in our marathon session. Will need some tidying.
I think it would be great to get these tidied and released.

On Thu, Jul 31, 2025 at 5:24 PM Judith Curry > wrote:
Thanks. I think Ross' version in msword is easier to work with, including the color coded comments.

On Thu, Jul 31, 2025 at 2:18 PM Fisher, Travis > wrote:
I'm attaching the version of the internal review comments that was compiled by the Office of Science. Note that I haven't checked to see if they numbered the reviewers the same way we did.

Even though we haven't had our introductory call yet, I'm also including Charles Park. Let me know if you're available tomorrow afternoon for a call to introduce Charles.

And I just saw Steve's email—yes, we should compile the anonymous reviews and your responses, and we should strongly consider releasing that document (and I believe we would have to if anyone requests it).

From: Judith Curry >
Sent: Thursday, July 31, 2025 5:06 PM
To: Roy Spencer >
Cc: Ross McKittrick >; John Christy >; Steven Koonin >; Josh Loucks >; Cohen, Seth >; Fisher, Travis >
Subject: [EXTERNAL] DOE reviews

Ross, if you can send me the latest version of the 8 DOE review responses, i can clean those up, verify changes were made, and send around for approval. Would be good to get those out of the way before the public comments

On Thu, Jul 31, 2025 at 12:27 PM Roy Spencer > wrote:

Ironical that no one cared when MY work was mischaracterized by the 97-Percenters' as being part of the 3%, even though by their criteria I was part of the 97% consensus.

I complained, but all they said was, "well, we put you in the 3 percent category".

The bias is rampant.

-Roy

From: Ross McKittrick >

Sent: Thursday, July 31, 2025 11:27 AM

To: Roy W. Spencer >; Judith Curry >; John Christy >; Steven Koonin >; Josh Loucks >; Cohen, Seth >; Fisher, Travis >

Subject: Fwd: Fw: Carbon Brief factcheck - your study has been cited in new US DoE 'critical review'

John and I got this from Tim Vogelsang at MSU. Carbon Brief is contacting everyone whose work was cited trying to gather up claims of misrepresentation. As Tim notes, there is no option on the form for saying your work was correctly characterized.

From: Vogelsang, Timothy >

Sent: Thursday, July 31, 2025 12:19 PM

To: Ross McKittrick >; John Christy >

Subject: RE: Carbon Brief factcheck - your study has been cited in new US DoE 'critical review'

CAUTION: This email originated from outside of the University of Guelph. Do not click links or open attachments unless you recognize the sender and know the content is safe. If in doubt, forward suspicious emails to IThelp@uoguelph.ca.

If you look at the pdf I was sent with the instructions, there is no option to report that someone's research has been correctly characterized. That's not a very scientific factchecking exercise, is it!

Tim

From: Ross McKittrick >

Sent: Thursday, July 31, 2025 12:15 PM

To: Vogelsang, Timothy >; John Christy >

Subject: Re: Carbon Brief factcheck - your study has been cited in new US DoE 'critical review'

I've heard of Carbon Brief but only read snippets of their articles cited elsewhere. They seem to be heavily into promoting renewables.

It's interesting to watch the machine swing into gear. There is a public comment docket opening up and I expect there will be quite the avalanche of material submitted, which we will need to prepare responses to, all of which will form part of the public record. If the comments are substantive we'll readily make revisions. We responded to a lot of comments from the internal DoE staff during the pre-publication review stage. But some of the most hostile comments didn't provide any data or citations in support so we couldn't do anything with

Location

Microsoft Teams Meeting
View map

Guests

- Fisher, Travis - organizer
curry.judith@gmail.com
ross.mckitrick@gmail.com
 - John Christy - creator, optional
steven.koonin@googlemail.com - optional
roywspencer@hotmail.com - optional
 - Barrios, Audrey - optional
 - Park, Charles - optional
 - Loucks, Joshua - optional
 - Cohen, Seth - optional
- View all event details**

Invitation from Google Calendar

You are receiving this email because you are subscribed to calendar notifications. To stop receiving these emails, go to Calendar settings, select this calendar, and change "Other notifications".

Forwarding this invitation could allow any recipient to send a response to the organizer, be added to the guest list, invite others regardless of their own invitation status, or modify your RSVP. [Learn more](#)

From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Wednesday, July 2, 2025 12:09 PM
To: Steven Koonin
Cc: John Christy; Judith Curry; Roy W. Spencer; Travis Fisher; Josh Loucks; Seth Cohen
Subject: Re: AP on NCA reports disappearing

Likewise I don't think adding the sentence is helpful. If people complain that we have final authority over our own final text we can point out that that is the standard for NCA and IPCC so if people don't like it they should have brought the matter up long ago.

If the CWG report is currently going through Inter-Agency review, does that mean that we will soon have a stack of helpful comments to wade through and if so, will that be something needing to be done before the report is released mid-July? Perhaps Travis you could update us tomorrow.

On Wed, Jul 2, 2025 at 11:47 AM Steven Koonin <steven.koonin@gmail.com> wrote:

This illustrates the degradation of credibility taht occurs when authors have final review-authority over their own text."

Our report could be accused of the same thing, so we need something to mitigate that. Open the peer review comments to the public? Use AI to group/summarize them?

From: John Christy <climateman60@gmail.com>
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Subject: Re: AP on NCA reports disappearing

Hayhoe - the same person who led the climate model evaluation section of NCA4 but who owns a company that makes money off of selling climate model output.

Steve - I think we should add a line in our NCA5 review at the very end of the evaluation of NCA4's Fig. ES.5 (just above section 2, page 9) that says, "This illustrates the degradation of credibility taht occurs when authors have final review-authority over their own text."

John C.

On Wed, Jul 2, 2025 at 10:18 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

Well if Borenstein is down to getting scare quotes from Holdren and Hayhoe I'd say the story doesn't have much legs.

NCA5 "really is the primary source of information for any city, state or federal agency who's trying to prepare for the impacts of a changing climate," said Texas Tech climate scientist Katharine Hayhoe

I doubt even her own town, much less state, uses NCA5 for planning purposes.

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<https://apnews.com/article/climate-change-national-assessment-nasa-white-house-057cec699caef90832d8b10f21a6ffe8>

The media are heating up on all of this. I hope they'll focus on the factual content of what we've written, but doubt that they will.

Steve Koonin

From: Judith Curry <curry.judith@gmail.com>
Sent: Wednesday, July 2, 2025 12:07 PM
To: Steven Koonin
Cc: John Christy; Ross McKittrick; Roy W. Spencer; Travis Fisher; Josh Loucks; Seth Cohen
Subject: Re: AP on NCA reports disappearing

I don't think adding that sentence will help. We can include recommendations re peer review in section 8.4

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Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

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Sent: Wednesday, July 2, 2025 12:07 PM
To: Steven Koonin
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Subject: Re: AP on NCA reports disappearing

I'll have some updates on this tomorrow! We are likely going to open up a separate DOE comment portal for the DOE report (the May 28 CWG report), and we are also likely to put the report through internal DOE concurrence first.

If you all know of any particular people of offices within DOE that should be included, please flag them for me on our call. Even if you expect them to be antagonistic, I'd still like to include everyone who has the relevant expertise.

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From: Travis Fisher <travis.scott.fisher@gmail.com>
Sent: Wednesday, June 25, 2025 12:05 PM
To: Roy Spencer
Cc: Ross McKittrick; Cohen, Seth; Judith Curry; Steven Koonin; John Christy; Josh Loucks
Subject: Re: CO2 Coalition requests Trump admin. review of NCA5...

The briefing was just me, Audrey Barrios, and Roger Pielke Jr. after the students left. Closed door, etc. The Secretary wanted to be there but was called away for a security briefing in a SCIF.

As we approach the action date (TBD), the DOE team will develop a public affairs rollout plan. If/when you want to shift your attention to outreach, we would love your input on that. I imagine you all have extensive networks of the types of people we'd want to call on for support.

What would be a good time to meet next week to discuss next steps on the NCA5 critique? I may also have an update on the ongoing rulemaking process, but as of today I don't have any news.

I'll propose midday Wednesday (July 2), noon ET to 1pm or 1:30.

On Wed, Jun 25, 2025 at 10:59 AM Roy Spencer <roywspencer@hotmail.com> wrote:

I don't understand why Will allows his work with vanWijngaarden to be misrepresented; after all of their line-by-line calculations they still got a 2XCO₂ radiative forcing in line with what the climate models radiative codes get.

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Will **believes** warming will be weak (as does Dick), but that's a feedback issue, not forcing (which their paper demonstrated).

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Sent: Wednesday, June 25, 2025 10:24 AM
To: Travis Fisher
Cc: Cohen, Seth; Roy Spencer; Ross McKittrick; Steven Koonin; John Christy; Josh Loucks
Subject: Re: CO2 Coalition requests Trump admin. review of NCA5...

I just finished reading the entire Lindzen/Happer report. Interestingly, the second half of the report mainly cites SK's book. Other than that, a bunch of words that aren't very effective.

p.s. Secy Wright picked the right committee

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Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

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I'll do a read through of this and see if it points us to any good examples that we can use. A lot of this is generalities

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From: John Christy <climateman60@gmail.com>
Sent: Wednesday, June 25, 2025 9:36 AM
To: Ross McKittrick
Cc: Roy Spencer; Judith Curry; Steven Koonin; Travis Fisher; Josh Loucks; Seth Cohen
Subject: Re: CO2 Coalition requests Trump admin. review of NCA5...

Looks like the NCA5 presented some fat targets for everyone.

John C.

Sent from my iPhone

On Jun 25, 2025, at 6:21 AM, Ross McKittrick <ross.mckittrick@gmail.com> wrote:

Here's the letter

<https://justthenews.com/sites/default/files/2025-06/PPT-CO2-NCA-5-Request-for-Correction.pdf>

On Wed, Jun 25, 2025 at 9:11 AM Roy Spencer <roywspencer@hotmail.com> wrote:

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Travis/Seth et al., should someone tell them? Or just ignore?

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Sent: Monday, June 23, 2025 9:24 AM
To: Cohen, Seth
Cc: Steven Koonin; Ross McKittrick; John Christy; Roy Spencer; Travis Fisher; Josh Loucks
Subject: Re: [EXTERNAL] write a policy piece?

After thinking about this overnite, here is my take:

Secy Wright selected us for our independence and scientific integrity (and apolitical). Post publication, the CWG team and each of us individually needs to come across as independent, transparent and authentic. The last thing we want to come across as being subsumed by the administration into puppets.

To my mind, this means that each of us individually (or in some subset group if we choose) should be free to publish academic journal articles on issues raised by our assessment. I think Steve was referring to the obviously broken interface between climate science and policy that has produced this deeply flawed NCA5 report with the apparent concurrence of the USGCRP, 14 govt agencies, and the NASEM. How did this come about, and what can we do about it? SK and I have both written extensively on these topics in our respective books.

With regards to post publication fallout, I intend to follow my normal MO of writing a blog post that reflects on my motive for getting involved with this, the process itself, my reflections on significant outcomes from this. This is what I do, part of my personal independence and authenticity as a scientist. I have also found my blog posts in the past to be very useful as a device to deflect journalists away from bugging me, i just refer them to the blog post. And SK's op-ed seems entirely reasonable to me. Of course, as a committee we will address substantive scientific comments/criticism. But journalists will be interested in the larger context of what this is and how it came about and its implications. I get that there is a press office that wants to handle this, but each of us is already in contact with many journalists who will undoubtedly contact us directly. And we don't want to come across as puppets for the admin, we should speak with our own authentic voices.

In the absence of any of us having signed anything (with possible exception of SK?) or having received any \$\$ for this, I would say that we are free agents here in terms of what we say about all this. Personally, I avoid any kind climate/energy policy advocacy and politics and will be scrupulous about that here, and will avoid any comments about DOE personnel or individual CWG team members

Obviously a topic that needs more discussion as we approach publication date

On Sun, Jun 22, 2025 at 10:50 AM Cohen, Seth <seth.cohen@hq.doe.gov> wrote:

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.....

I would strongly advise that w let the scientific community ask those questions and then provide answers, not the other way around. Affirmatively rebutting concerns will, optically, suggest that we see something worth addressing (the lady doth protest too much). When we can let the work speak for itself, we're in a much better position.

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Sunday, June 22, 2025 1:17 PM
To: Ross McKittrick <ross.mckittrick@gmail.com>
Cc: John Christy <climateman60@gmail.com>; Cohen, Seth <seth.cohen@hq.doe.gov>; Judith Curry <curry.judith@gmail.com>; Roy Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Josh Loucks <loucksj14@gmail.com>
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We should also think about op-eds, blog posts for circa Jul 13

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Steve Koonin

<~WRD0000.jpg>

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From: Steven Koonin [steven.koonin@gmail.com]
Sent: 6/22/2025 9:58:06 PM
To: 'Travis Fisher' [travis.scott.fisher@gmail.com]; 'Ross McKittrick' [ross.mckittrick@gmail.com]
CC: 'Judith Curry' [curry.judith@gmail.com]; 'John Christy' [climateman60@gmail.com]; 'Seth Cohen' [seth.cohen@hq.doe.gov]; 'Roy Spencer' [roywspencer@hotmail.com]; 'Josh Loucks' [loucksj14@gmail.com]
Subject: RE: [EXTERNAL] write a policy piece?
Attachments: ~WRD3037.jpg; Endangered! 2.0.docx

Yes, we should avoid policy fights. I think that's the natural inclination of all of us authors – we like to talk about facts. And I hope we'll be able to continue to do that.

Back around Memorial Day, I drafted the attached OpEd. (Now three weeks later, I'd only change it a bit.) I'm not about to submit this anywhere, but I think it's the kind of content that would be acceptable, either with a solo byline or with co-authors.

SEK

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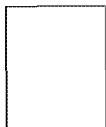
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The Real Danger of Carbon Dioxide Emissions

“It ain’t what you don’t know that gets you into trouble. It’s what you know for sure that just ain’t so.” – attributed to Mark Twain

By Steven E. Koonin

A new climate science assessment from the Department of Energy challenges the widespread belief that greenhouse gas emissions pose a serious threat to national wellbeing. You might think this would reassure both those alarmed by imagined climate catastrophes and those frustrated and impoverished by forced energy transitions. Time will tell.

Secretary of Energy Wright has a deep understanding of climate science and recognizes the disconnect between public perceptions, past government reports, and the science itself. To provide policymakers with clearer insights, he commissioned an independent assessment by a team of five senior scientists, including myself. Collectively, we bring over two centuries of research experience, almost all of which is directly relevant to climate studies.

The resulting report, *Impacts of Carbon Dioxide Emissions on the U.S. Climate*, is entirely the work of its authors, free from political influence—a departure from previous assessments. It draws upon UN and U.S. climate reports (examining the full studies rather than their summaries), peer-reviewed research, and primary observations. The findings reveal a U.S. climate shifting in ways largely consistent with natural variability, with future changes more likely to be a nuisance than a catastrophe.

Some key conclusions, each supported by citations, include:

- Elevated CO₂ levels enhance plant growth, contributing to global greening and increased agricultural productivity.
- Complex climate models provide limited guidance on CO₂’s impact, but simpler approaches based on direct observations suggest the climate is less sensitive than most detailed models indicate. Overly sensitive models, often using extreme emissions scenarios, have exaggerated future warming projections.
- Data shows no significant long-term trend in most extreme weather events. Claims of more frequent or intense hurricanes, tornadoes, floods, and droughts in the U.S. are not supported by historical records.
- While global sea levels have risen about eight inches since 1900, aggregate U.S. tide gauge data does not show any long-term acceleration in the rate of rise.

- Natural climate variability, data limitations, and model deficiencies complicate efforts to attribute specific climate changes or extreme events to human CO₂ emissions.
- Both models and real-world experience suggest human-caused warming will have a smaller economic impact than widely believed. Overly aggressive mitigation policies could do more harm than good.
- Even the most ambitious reductions in U.S. emissions would have little effect on global emissions, with an even smaller impact on climate trends.

That these findings might surprise many speaks to failures in communicating of climate science to the public. The DOE report highlights several instances of miscommunication that have contributed to misconceptions.

The report is currently in draft form and open for public comments for six months. The author team will review substantive feedback, respond to serious critiques, and update the draft as needed. This process will not only refine the report but also encourage an overdue scientific debate on the climate impacts of greenhouse gas emissions.

The final report will support balanced, evidence-based climate policies—policies that weigh the risks and benefits of both natural and human-driven climate change against the costs and disruptions of proposed climate actions. Anything less risks causing more harm to society than the changing climate itself.

Mr. Koonin is a Senior Fellow at Stanford's Hoover Institution and the author of "Unsettled: What Climate Science Tells Us, What It Doesn't, and Why It Matter."

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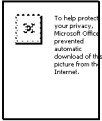
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Sent: Sunday, June 22, 2025 3:15 PM
To: Judith Curry
Cc: Steven Koonin; John Christy; Seth Cohen; Roy Spencer; Travis Fisher; Josh Loucks
Subject: Re: [EXTERNAL] write a policy piece?

Whether we comment individually or as a group it will be paramount to avoid saying anything that would allow potential future litigants to claim we were working towards foregone or predetermined conclusions. As matters transpired we have not been involved in the EPA EF process nor were we informed about or involved in any of their regulatory moves (e.g. Clean Power Plan) so we have clean hands, but my overall preference is to bring forward information about the process as needed to rebut stated criticisms once they appear, rather than trying to anticipate and pre-empt them.

On Sun, Jun 22, 2025 at 2:51 PM Judith Curry <curry.judith@gmail.com> wrote:

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To: Steven Koonin; Ross McKitrick
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Subject: RE: [EXTERNAL] write a policy piece?

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I would strongly advise that we let the scientific community ask those questions and then provide answers, not the other way around. Affirmatively rebutting concerns will, optically, suggest that we see something worth addressing (the lady doth protest too much). When we can let the work speak for itself, we're in a much better position.

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I can see both sides of this.

-Roy

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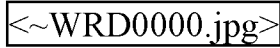
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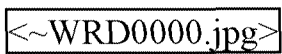
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Attachments: Untitled attachment.htm; NCA5_Zero_Comments_v02.pdf; Untitled attachment.htm; NCA5_3OD_comments_2023_Ch_2.docx; Untitled attachment.htm; NCA5_3OD_comments_2023_Ch_3.docx; Untitled attachment.htm; NCA5_3OD_comments_2023_Intro.docx; Untitled attachment.htm

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> Sent: Sunday, June 22, 2025 12:08 PM
> To: Steven Koonin <steven.koonin@gmail.com <<mailto:steven.koonin@gmail.com>>>
> Cc: Roy Spencer <roywspencer@hotmail.com <<mailto:roywspencer@hotmail.com>>>; Ross McKittrick <ross.mckittrick@gmail.com <<mailto:ross.mckittrick@gmail.com>>>; John Christy <climateman60@gmail.com <<mailto:climateman60@gmail.com>>>; Travis Fisher <travis.scott.fisher@gmail.com <<mailto:travis.scott.fisher@gmail.com>>>; Josh Loucks <loucksj14@gmail.com <<mailto:loucksj14@gmail.com>>>; Cohen, Seth <seth.cohen@hq.doe.gov <<mailto:seth.cohen@hq.doe.gov>>>
> Subject: [EXTERNAL] Re: write a policy piece?
>
> Interesting idea
>
> We should also think about op-eds, blog posts for circa Jul 13
>
> On Sun, Jun 22, 2025 at 8:29 AM Steven Koonin <steven.koonin@gmail.com <<mailto:steven.koonin@gmail.com>>> wrote:
> Should we collectively author a policy piece to be submitted to, say, Science mag's Policy Forum.

> <https://www.science.org/action/doSearch?AllField=policy+forum>
>
> It could be titled something like “Reflections on the National Climate Assessment”
>
> Would they dare publish it? Since our critique will have the status of an official USG document, that might help.
>
> If not Science, then perhaps we could try Issues in Science and Technology?
>
> Steve Koonin
>
>
>
> --
> <~WRD0000.jpg>
> Judith Curry, President
> CFAN - Climate Forecast Applications Network
> Reno, NV USA
> curry.judith@cfanclimate.com <<mailto:curry.judith@gmail.com>> | +1.404.803.2012
> <http://www.cfanclimate.n> <<http://www.cfanclimate.com/>>et
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> *****
> This message does not originate from a known Department of Energy email system.
> Use caution if this message contains attachments, links or requests for information.
>
> *****

Steve

Look what I found on my laptop here in Juneau - my public comments on the NCA5 zero order draft and 3rd order draft. There are some familiar themes here that were obviously ignored. Ross probably has his comments handy too. These can be kept in the back pocket if ammo is needed.

John C.

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville
climateman60@gmail.com

Comments on Fifth National Climate Assessment (NCA5)
Zeroth-order Draft
20 Feb 2022

John R. Christy
Alabama State Climatologist
Distinguished Professor, Atmospheric and Earth Sciences
Fellow, American Meteorological Society
The University of Alabama in Huntsville

To whom it may concern

As this appears to be an outline of the NCA5, my comments will of necessity be rather general and assume that many of the characteristics of NCA4 will likely be seen in NCA5. Though the research and economic development work I perform touches all 31 sections, I will focus my comments on the science of climate.

In the NCA5, credibility will be enhanced if the report publicly corrects highly misleading information that appeared in NCA4.

As a document of record, NCA4 failed in many places to provide information that could stand up against objective analysis. As a result, it would not be considered as admissible evidence or even as defensible science in the public arena. It can be easily shown in public debate (or in the court room), the NCA4 came across more as a persuasion-piece while neglecting the considerable and published research that contradicts or diminishes many of its conclusions (see following section).

The most egregiously erroneous claim of which I'm aware in NCA4 was Fig. ES.5 and its accompanying title which declares "Record Warm Daily Temperatures Are Occurring More Often". As shown in a number of analyses, this figure title is absolutely false and the figure intentionally misleading because record high temperatures are NOT occurring with greater frequency. Indeed the "Heat Wave" chart shown later should have been highlighted instead. In Fig. ES.5, the quantity in each year does not represent an apples-to-apples comparison through time. Each year uses different data. However, when all of the data are used properly and systematically for each year's calculation, there is actually a *downward* trend in the occurrence of daily record high temperatures, rendering the claim of increasing record high temperatures not just misleading, but objectively false. The only reason the ratio (a poor metric) is increasing (for high vs. low records) is that low records are becoming less frequent due in large part to surface development around the weather stations and the associated warming of TMin (many papers on this).

Perform due diligence in investigating alternatives to the claims that, though they are popular, do not stand up to criticism.

In other words, the authors should view this report as one that contains claims, all of which have been tested by objective cross-examination. In the past the NCA's have grown accustomed to making claims, finding a "peer-reviewed" paper that supports it, neglecting contradictory information, and moving on because no one was really watching.

"Peer-Review" is a feature of a paper and does not guarantee the information is accurate nor that other papers and information are published that contradict it. For example, the paper by Hausfather et al. 2020 (GRL), that claims climate models are reasonably good, is tempting for NCA5 to cite as evidence supporting climate models as useful tools. However, it doesn't take much to show the study has numerous faults and in fact other papers come to the opposite conclusion (and thus should be cited). Due-diligence (or lack thereof) of the claims made in NCA5 is what scientists like myself will be watching carefully and will be forced to expose (if negligent) as time goes on as we seek to defend the scientific enterprise as a whole.

In the case of Hausfather et al. 2020 (hereafter H20), the very first problem is the choice of variable – surface temperature (Tsfc). Tsfc is a variable already heavily tuned in the models and so is not a test-metric for model physics and fidelity against observations. There are several notable statements on this, but the one by Mauritsen and Roeckner 2020 is clearest "We have documented how we tuned the MPI-ESM1.2 global climate model to match the instrumental [Tsfc] record ...". They went on to explain they dialed the cloud feedbacks (their uncertain variable-of-choice), to get the right answer because their original result was well out of physical possibilities. This is not science, this is curve fitting. Also, regarding H20, see here for errors in the statistical analysis and in the code that were discovered but never corrected in the literature and which rendered H20's conclusion unsupportable: <https://judithcurry.com/2020/01/17/explaining-the-discrepancies-between-hausfather-et-al-2019-and-lewiscurry-2018/>

A better test-metric for models is a physical variable that fundamentally expresses the response to extra GHGs in every model in the same way. Such a variable is the bulk tropical atmospheric temperature as its value is a consequence of the moist thermodynamics of the real atmosphere (which must be correct for any predictive exercises). As is well-known and published, models on average produced significantly too-high warming rates which indicates something fundamentally is wrong with the physics of the models (since their surface temperatures are not too bad due to tuning). If you get Tsfc mostly right, but err significantly in the atmosphere above, something is very wrong with the thermodynamics. See Mitchel et al. 2020, McKittrick et al 2020, Christy and McNider 2017 and citations therein. This is an example where a scientifically defensible statement in NCA5 should show published results that are at odds with claims that models are useful for policy and thus suitable for all of the following sections of the report that use model output. If NCA5 demonstrates serious model problems (which is the scientifically-defensible thing to do), does the NCA5 have much to report? Are the NCA5 authors able to be coldly objective or are there vested interests at play? Something to think about.

The IPCC itself, while not drawing attention to this significant tropospheric problem, supplies considerable information to convince one to discount model output. Note that models are simply hypotheses because the numerous physical components of the climate system are approximated with “hypotheses” about how each behaves, e.g. how and when do clouds form? None are perfect, most are crude and in combination, they are not accurate enough for policy utility. A good example of this is IPCC AR6 Fig. 3.8 in which the model Tsfc response to natural variability, aerosols and GHGs is shown. The models don’t agree amongst themselves at all, demonstrating that fundamental components of the physical system are not known accurately.

First in Fig. 3.8, the models’ natural variability is essentially zero which is not verified by the Tsfc record prior to 1970. But take HadGEM3 as an example of the other forcings. The range of response to aerosols is -1.0°C to +0.1°C with HadGEM3 at -1.0 °C. (Note that the range of aerosol response is fully 100% about the average – something an objective report would notify its readers so they would be aware of model imprecision). Follow this with HadGEM3’s GHG response of +2.0 °C (on a range of 1.0 to 2.2 °C) and then the combined HadGEM3 result is a “just right” value of the total response of about 1.0 °C. This is a terrific example of tuning as well. An objective NCA5 would include this chart from the IPCC and document for the readers the lack of understanding in the physics of and thus response to, (a) natural variability, (b) aerosols and (c) GHG forcing.

In the NCA5 regional report I encourage the authors to read “A Practical Guide to Climate Change in Alabama” in which I show many results (for the SE and the entire conterminous US as well), including the complete failure of climate models to depict the temperature record of the state. This result in Fig. 7 is an update of Christy and McNider 2016 (J. App Meteor & Clim) but now uses CMIP6 models. Other charts will be illuminating:

https://www.nsstc.uah.edu/aosc/climatechangePDF/AlabamaClimatePracticalGuide_lowres.pdf

Clearly show the evidence for climate model inadequacies on many scales and many variables as they often misrepresent the real climate system because it is composed of two coupled, turbulent fluids (atmosphere and ocean) which generate a complex and infinite variety of patterns without human forcing.

For example, Key Topic 2 should read “Advances and concerns in observations and modeling”. As it stands, the Key Topic 2 implies only positive results have come about through time when the fact is the spread of climate sensitivities has expanded (ECS of 1.8 to 5.6 °C) indicating great concern and modelers are opening acknowledging (finally) the imperfections of this part of climate science (e.g. <https://www.wsj.com/articles/climate-change-global-warming-computer-model-11642191155>). Describing model results in terms of advances and improvements belies the fact models have always had and continue to have serious issues with the major components of the climate system – and their agreement with each other is actually worsening.

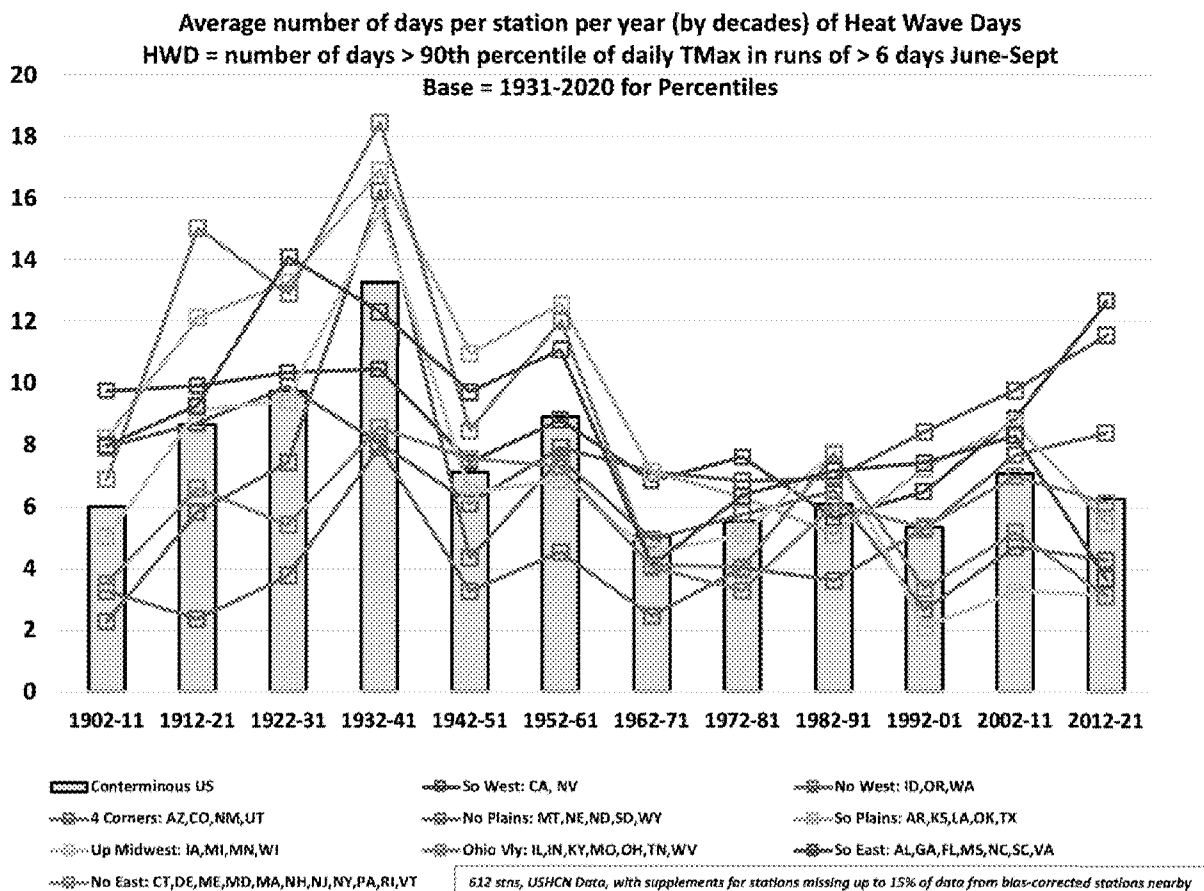
Also, see comments above related to some specific model issues that are well-known and thus allow the scientifically-justifiable skeptical eye (hopefully someone on the author team falls into this category) to look at these models, ask the hard questions, and display the results. One obvious point, as noted, is that the CMIP6 models have generated even more uncertainty than CMIP5 with ECS values ranging from 1.8 to 5.6 C. This is clear evidence the modeling enterprise is leaning way out in front of its skis. Then, there are two different problems with models here. First, many of the simulations have too much response (high ECS) and secondly, many of the published reports use unrealistically high GHG scenarios. So, with too high ECS and then too high GHG forcing – the result is a compounded erroneous and irresponsible result. Nothing from scenarios above pathways of 6 W should be shown as “plausible” because they aren’t happening and won’t happen.

Don’t twist data to minimize past episodes of heat

As is well known, US (conterminous) heat extremes show no changes in the past 120 years. This is shown when assessing changes in daily maximum temperatures, whether considering runs of extremes or number of daily records or “all time” records, etc. Daily minimum temperatures are too contaminated by surface development around the weather stations, so the best information will come from daily high extremes.

Below is a table of “Heat Wave Days”, a simple metric that correlates with Russo et al. 2014 metric at +0.99. The advantage of this metric is that it is simple to understand and calculate. The metric is the number of days that occur in runs of at least 7-days in length for which the daily maximum temperature exceeds the 90th percentile for each day. The metric is the annual average of these days per station in each region. A value less than seven simply means many stations in that region had no HWDs and affected the average thusly. The annual, per-station averages are averaged per decade. The data base is the USHCN v2.5 station records. For several stations with at least 85% of data (for 1902-2021), supplemental data was supplied from a nearby station corrected for bias.

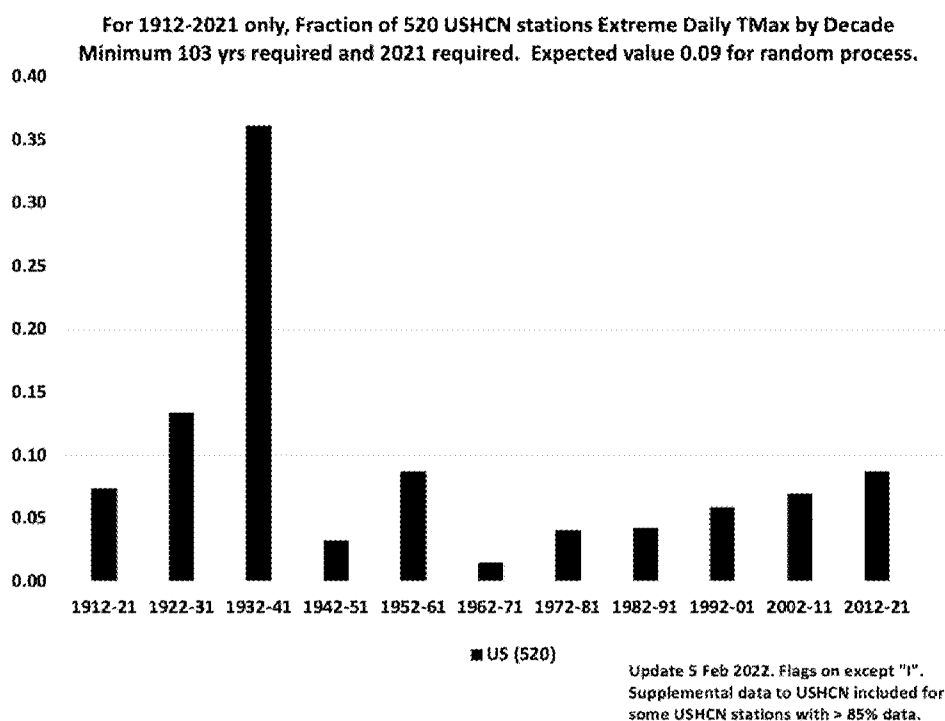
	So. West:	No. West:	4 Corners:	No. Plains:	So. Plains:	Upper Midwest:	Ohio Vly:	So. East:	No. East:	Conterminous US
1902-11	9.74	7.86	4.26	3.24	7.78	5.41	8.62	9.24	4.26	6.59
1912-21	9.14	8.57	2.84	6.24	14.05	10.19	15.24	8.62	6.67	9.10
1922-31	9.62	9.40	2.76	4.61	11.14	6.74	9.49	11.52	4.47	7.75
1932-41	11.83	8.37	7.90	17.56	19.08	17.67	21.05	15.30	9.14	14.79
1942-51	6.86	6.48	3.88	6.51	10.05	8.94	11.13	9.38	8.99	7.91
1952-61	7.65	6.42	3.94	6.04	14.14	6.14	11.87	12.51	7.21	8.70
1962-71	7.77	7.21	2.90	4.83	6.54	4.07	4.15	4.35	3.74	5.06
1972-81	8.15	8.30	3.39	6.16	3.88	5.43	2.56	3.36	3.16	4.81
1982-91	5.84	5.99	3.81	6.61	7.61	7.92	8.27	8.99	5.66	6.75
1992-01	6.34	9.19	4.83	2.68	5.46	2.01	4.29	7.72	5.49	5.16
2002-11	9.19	10.32	8.34	5.62	7.01	3.31	3.77	6.25	5.86	6.66
2012-21	10.26	9.06	6.51	3.34	9.44	3.01	4.65	6.76	6.63	6.61



So West: CA, NV
 No West: ID, OR, WA
 4 Corners: AZ, CO, NM, UT
 No Plains: MT, NE, ND, SD, WY
 So Plains: AR, KS, LA, OK, TX
 Up Midwest: IA, MI, MN, WI
 Ohio Vly: IL, IN, KY, MO, OH, TN, WV
 So East: AL, GA, FL, MS, NC, SC, VA
 No East: CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VT

The evidence above indicates heatwaves are not increasing at all. The 2021 heatwave in the Pacific NW is represented where one can see that the most recent decade (2012-2021) has a value (11.59) which is higher than the previous 11 decades. However, for the nation as a whole, 5 of the 8 regions were at or below the average, with the nation as a whole being less than the overall average for 2012-2021. Similar results are obtained for the number of daily record high temperatures that occur by decade. The required feature of these data is the consistency of the station records through the entire time series (there were 612 stations used above).

Don't be fooled by the *NYTimes* which has defrauded its readers by showing "record" charts that incorporate stations with as little as 30 years of data and only 50% availability, for example here. <https://www.nytimes.com/interactive/2022/01/11/climate/record-temperatures-map-2021.html>. OF COURSE most of those stations would observe their record high temperature only recently because they did not exist during, say, the 1930s or 1950s. Below is a calculation of the fraction of USHCN stations in the conterminous US which experienced their "all-time" (i.e. period of record 1912-2021) extreme daily maximum temperature. The expected value for random processes is 0.091 (i.e. 1/11 decades). As can be seen, the most recent decade was slightly below the expected value, and that there is a downward trend for the nation. Stations required a minimum of 103 years of data (out of 110 years) and must have data in 2021.



Fraction US (520) with Extreme TMax

1912-21 0.074
1922-31 0.134
1932-41 0.361
1942-51 0.033
1952-61 0.087
1962-71 0.015
1972-81 0.041
1982-91 0.042
1992-01 0.059
2002-11 0.070
2012-21 0.086

Consistency of the time series is a requirement, especially for a document such as NCA5. The evidence is very clear that neither heatwaves nor period-of-record extreme high temperatures have increased. This should be featured in the NCA5 as a matter of scientific honesty as well as the fact it would be very interesting for the readers.

Ignore “mining-for-significance” (MFS) papers that purport to demonstrate recent dramatic climate change that implicate humans

A popular strategy today is to “mine” a set of observations to discover some set of parameters from which, by varying their magnitudes and durations, one might “discover” that the metric is significantly different from the past. Others might want to call this “cherry-picking” and Wikipedia calls it “data-dredging” but it often is known as MFS (which has been a problem found in the medical field most often, e.g. Smith and Ebrahim 2002 doi: 10.1136/bmj.325.7378.1437).

An excellent example of MFS was just published in *Nature Climate Change* with a title, “Rapid Intensification of the emerging southwestern North American megadrought in 2020-2021” and the associated claim that produced several similar headlines “2000-2021 was the driest 22-year period since at least 800” (Williams et al. 2020).

Three brief points can indicate this is not a remarkable result. First is the use of a carefully selected period “22 years”. This was done purposefully to avoid the wetness of the late 1990s in the West which would have overturned the dramatic headline. In other words, the headline fails at just 25 years and certainly at 30 or 50 years. This is a clear example of MFS.

Secondly, that Williams et al. 2022 claim that the last 22 years constitutes a “megadrought” ignores the notion of what a megadrought is. Probably the most recent western megadrought ended in the 14th century when the length and duration of that drought in the Sierra Nevada caused alpine lakes to recede so far for so long that 50-100 year old forests grew in the then-dry lakebeds. An example is Cliff Lake in Fresno County, CA in which the lake level was at least 5 m lower than it is today for a period long enough for mature trees to be established which are now under water (e.g. Morgan and Pomerleau, 2012 doi:10.1007/s10933-012-9590-9). In other words, California is not in a megadrought.

Thirdly, the modeling exercise that attempted to implicate humans is pointless because the models could not reproduce the natural variability of the precipitation regimes in the West – for example, it could not be demonstrated at all that the models could produce the variations of the past 100 years nor of the megadroughts of the 14th and earlier centuries. Statistically then, the paper’s methodology is not scientifically defensible because the model “reference” is incompatible with the real world (i.e. the “control” run of the models did not represent the “control” run of the real world, hence the experimental results do not apply to the real world). For diagrams showing the poor

character of model natural variability, refer to the earlier work by Williams et. al. 2020 Science, doi 10.1126/science.aaz9600, Fig. 6d-6g which demonstrate complete failure of models to produce natural variability.

If a paper such as Williams et al. 2022 is referenced in the NCA5, it should be cited as an example of poorly produced information. If it is referenced and not objectively criticized, then the “final say” on the utility of NCA5, as determined in the public sphere, will be negative as it will be demonstrated that the authors found themselves unable to be objective, but rather cited only papers that satisfied a particular point of view.

Avoid Conflict of Interest.

The clearest example of this of which I’m aware (I’m sure there are others) is Katharine Hayhoe who was a key author of NCA4 and its climate model evaluation section. As she is also the owner of a company whose revenue depends on clients believing that climate model output is profitable, this entire section can be dismissed as biased and inadmissible because of a demonstrable, clear and direct conflict of interest. And indeed, the section did not report on real, published and substantial model problems with any scientific diligence.

A second, broader matter of conflict-of-interest is the unusual power given to the authors as having “final say” on the material to be included and how claims are stated. In other words, it is likely that they are placed in the position of judging their own work-and-biases against evidence which contradicts these. This is not true “peer review”. My advice in approaching this is to remember that the authors will not, in fact, have the “final say” in the public arena. When the report is made public, problem areas, i.e. where due diligence and strict, objective, scientifically-defensible processes were not applied, will certainly be exposed. Perhaps when preparing this report, each author should think that a cross-examiner, more knowledgeable than they are, is looking over their shoulder, ready to pounce if the work is not objectively represented. Everyone has a bias, and the list of authors I see here is heavily (if not completely) weighted toward one view of the issue, which fosters “group-think” to a high level. But it is possible to be independent I believe. To serve the tax-paying public, evidence that contradicts prevailing opinions must be included – and there is plenty of it.

John R. Christy
The University of Alabama in Huntsville
27 January 2023

Comments on NCA5 Third Order Draft (3OD)

Chapter 2

There is a convolution of “confidence-claims” in the document between two ideas; (1) knowing “what” has happened versus (2) “why” it has happened. There is more confidence in the “what” since we have instrumental records to document changes (many of which are not reported properly in this document). However, the “why” is far less well-known (unequivocal?, p.2-3). This lack of understanding is simple to demonstrate since knowing how a system “unequivocally” behaves necessarily implies essentially perfect predictive capability for the system as a whole and for its major components. As will be shown, especially in comments on Chapter 3, the current understanding and predictive capability are rather poor.

The document has a virtual blind spot as to the role of natural variability and this is most evident when discussing the climate of the United States with a narrow focus on only the last 40 to 70 years. This deliberately, I believe, diverts attention from the major climate variations of the first part of the 20th century (the “what” that we know) which could only have been caused by natural variability (i.e. the “why”). To say “Climate is Changing, and scientists understand why” is a claim without sufficient foundation (it fails the predictive rule as will be shown).

This is not to say that some of the changes we see are not tied to increases in greenhouse gases (GHGs) because GHGs have no choice but to be thermally active. However, the evidence indicates the real climate system has feedbacks which mitigate the full force of this effect and have little influence on extreme events in any case as will be shown. Further, if “scientists understand why” extreme events happen, then how does one explain the inability of these “scientists” (if they exist) to model the greatest West Coast atmospheric river event of the instrumental record (1861-1862) or the heat wave records of the 1930’s and 1950’s? The answer – “they” actually don’t know “why.”

Heat *****

3OD P. 2-9. Claim: US warming faster than the global average. The temperature trend utilized here convolves two somewhat disparate quantities – the average of the daily maximum (TMax) and daily minimum (TMin). As has been shown in many publications, TMin is highly contaminated by the growth of infrastructure around the stations, no matter how minor, and is thus not an indicator of the background climate which this report should examine (e.g. Christy et al. 2006, 2009, Christy 2013, Kim and Christy, 2022 and numerous references therein). To capture the background climate for use here, one should focus on TMax. As well, the report

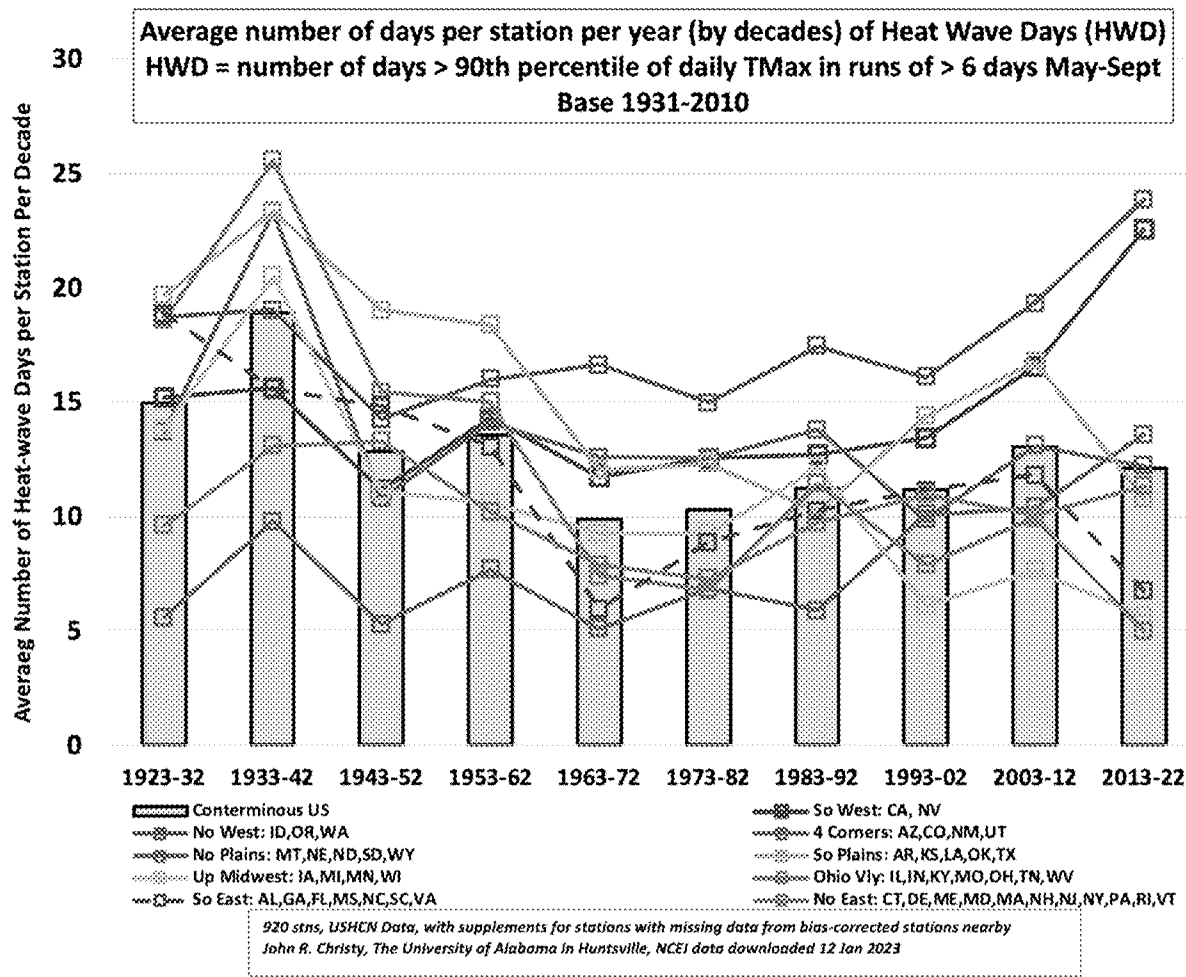
could also point out the urban climate is definitely warming (and different from a pristine climate) and that has implications, some of which are already discussed in the NCA.

To assess what I will call the “background climate”, or that which is more closely tied to the response to extra GHGs, one should investigate the temperature of the troposphere where the response is largest and unaffected by urbanization. The trend of the US (with Alaska) tropospheric temperature (UAH TLT, Christy et al. 2018) is +0.18 C/decade and that of the globe is +0.13 C/decade since 1978. So, yes, the air over the US is warming faster than the global average, but not by much at all. How much of this is due to natural variability? If one simply removes the cooling effect in the first part of the record of the volcanoes, the global trend drops to about +0.10 C/decade (Christy and McNider 2017), a relatively minor rate of change.

3OD P. 2-15. “Heatwaves Have Become More Common.” This is probably the most egregious of the 3OD claims as it is “deceptive truth” in that it keeps from the reader the full and contradictory facts of the situation. In the US, multi-day heat waves in extreme high temperatures are not becoming “hotter, more frequent, larger and longer lasting” when starting in the early 20th century. This was NOT done by Lyon and Barntson, 2017 (b. 1979), Keellings and Moradkhani 2020 (b. 1981) and Rogers et al. 2022 (b. 1979). So, the heading, to be scientifically accurate, should state

“Heatwaves have become more common if you ignore the period before 1980.”

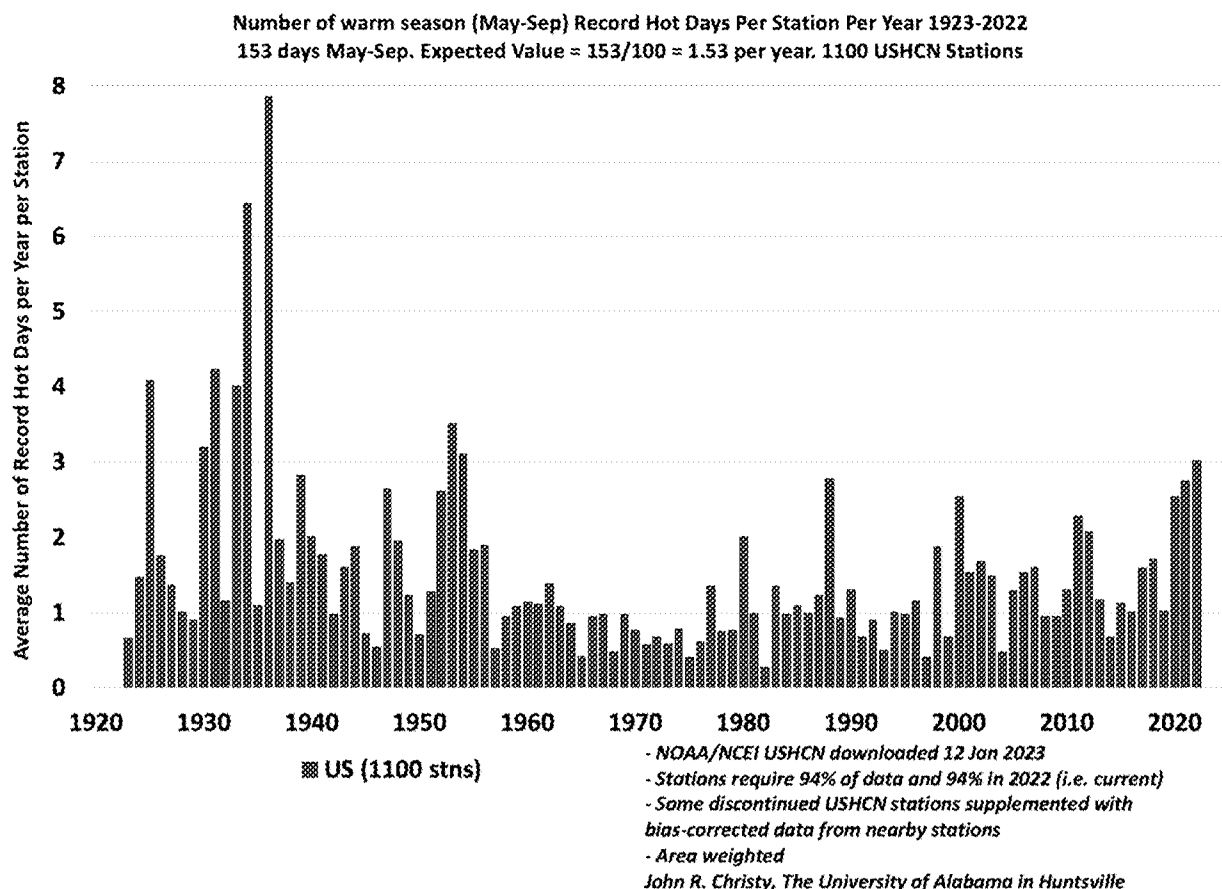
The following chart, JRC Fig. 1 (I will preface my figures with “JRC” to separate from the NCA 3OD figures) uses NOAA/NCEI USHCN stations (for some discontinued stations, nearby bias-corrected stations were substituted much as NCEI did with “threaded” stations). This metric (number of days in 7-day or more heat waves) correlates with Russo et al. 2014 metric of heat wave intensity used in USGCRP CSSR at 0.98.



JRC Fig. 1 The average number of “heat-wave” days by decade (days in runs of at least 7 days in a row in which each value is hotter than the 90th percentile for that date.). NOAA/NCEI data.

The evidence is clear that Heatwaves in the conterminous US have not increased. Indeed, the most recent decade (2013-2022) is slightly below the long-term average. While the West has experienced some major events in the last decade, the rest of the country has not, even achieving the lowest number of heatwave days in the century-long record in two regions (Ohio Valley and Upper Midwest).

Further, the incidence of daily record high temperatures is not increasing at all. This is demonstrated in JRC Fig. 2 below when using a very short time period of only 100 years (1923-2022).



JRC Fig. 2. Number of daily record high temperatures per station per year from 1100 USHCN stations with at least 94% of data (median is 98%) and which are current through 2022. NOAA/NCEI data.

Thus, the 3OD misleads the readers by improperly selecting a particular period that satisfies a claim that heat is becoming worse while ignoring evidence that the claim is actually false.

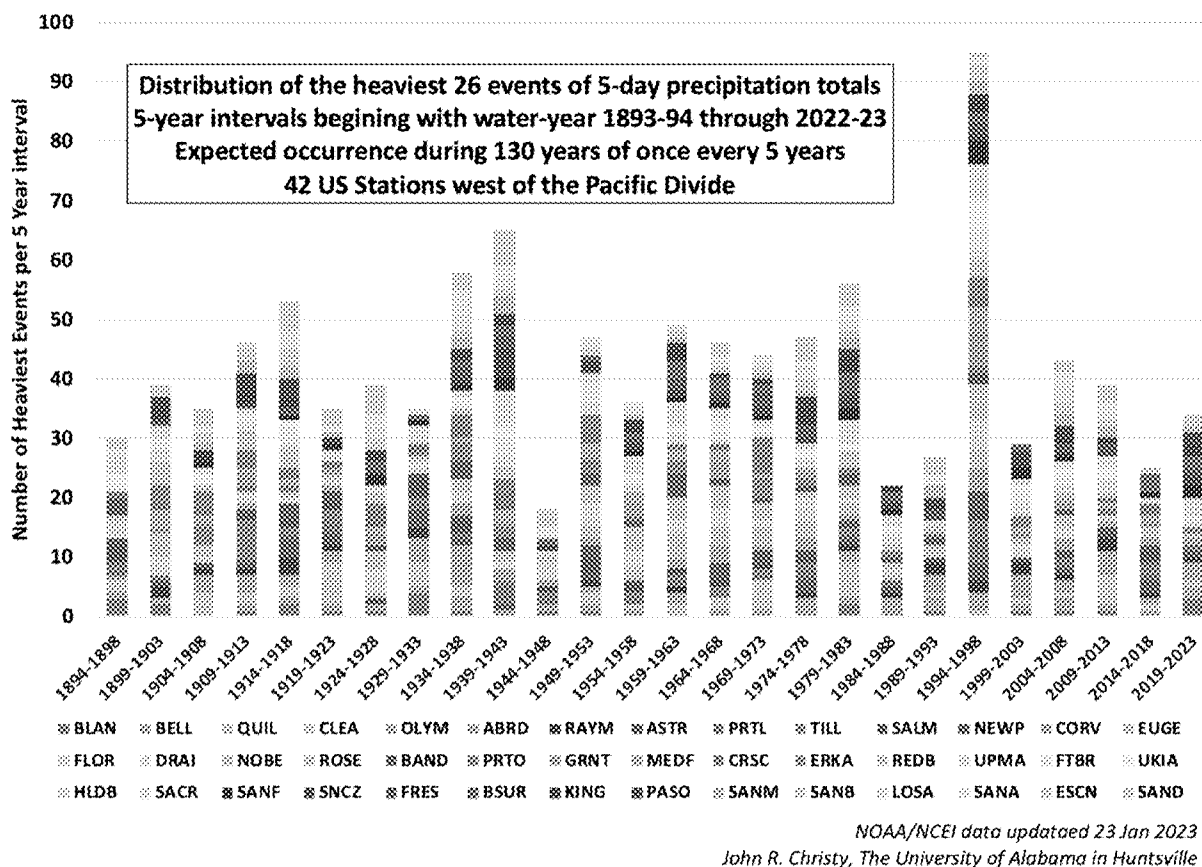
Extreme Rainfall *****

3OD p. 2-15,16. Rainfall is becoming more extreme and flood risk is increasing. Again, the authors focus on a “too-short” time period to support their views (since 1958) and show in 3OD Fig. 2.7 an increase in “extremes” in all regions for a few metrics. This is a highly misleading diagram and will fail close inspection.

First, McKittrick and Christy 2019 tested these NCA claims and found that if the trends are begun at specific points-in-time (e.g. 1901 or 1958 as NCA has always done) some are mildly significant. However, when using longer or shorter periods (e.g. as in 150 or 40 years, McKittrick and Christy) the “significance disappears”. McKittrick and Christy 2019 is a heavily peer-

reviewed paper that was not mentioned in the 3OD but should as it directly contradicts the NCA claims and the public should be aware of this.

Additionally, using the same data from McKittrick and Christy, but updated to deal with these claims here, I have focused on 42 Pacific Coast stations with complete daily precipitation records from water-year 1893-94 (through 20 Jan 2023 to include the 50-day Atmospheric River or AR event of 2022-23). All stations are west of the Pacific Coast Divide. JRC Fig. 3 is the distribution in time of the 26 heaviest 5-day event totals of the past 130 years (i.e. nominally the heaviest event per every five years.). These would represent the main impulse of a major AR event that would likely initiate flooding.

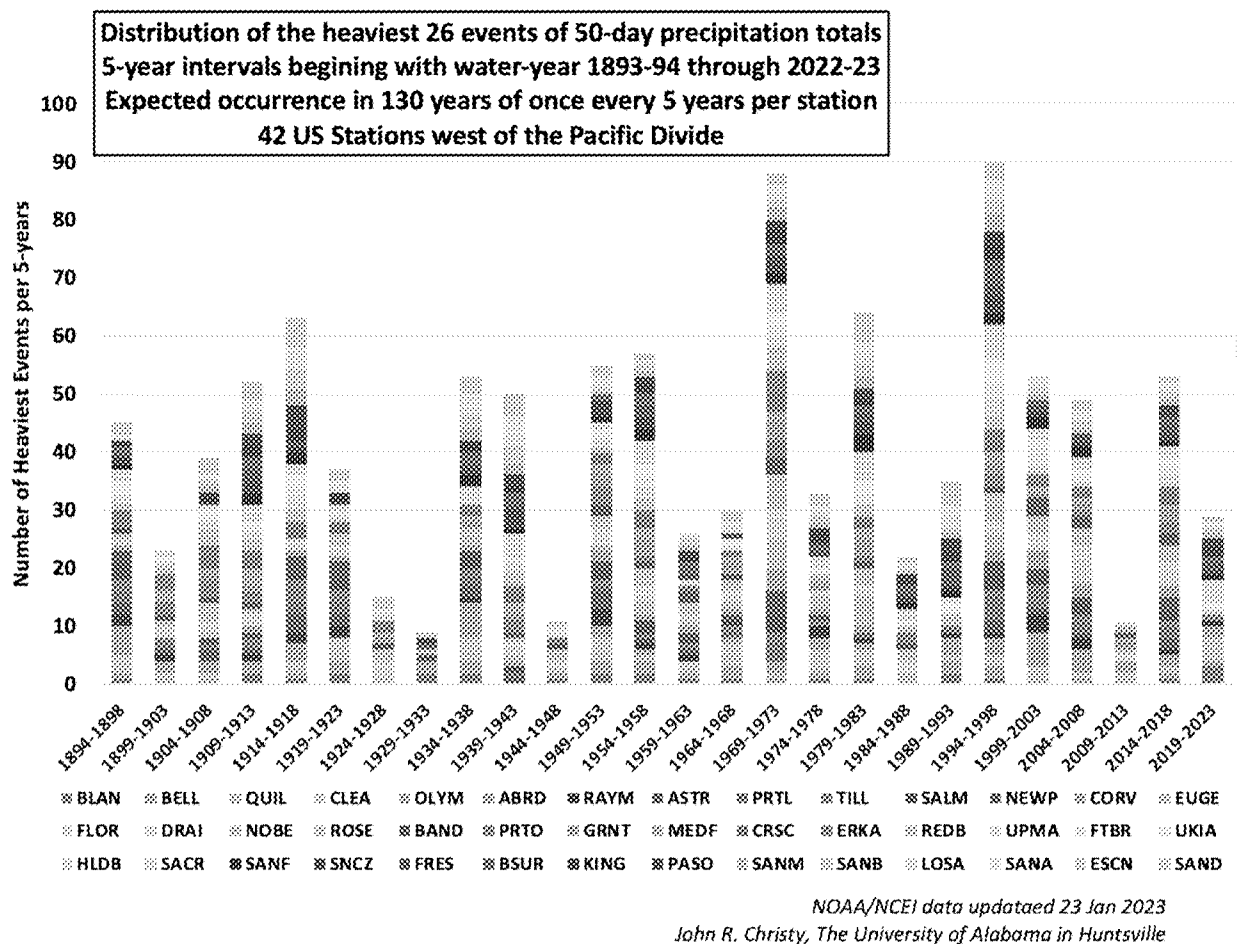


JRC Fig. 3. Distribution in time in 5-year intervals of the 26 heaviest 5-day precipitation events in 42 stations west of the Pacific Divide. A “year” is the water-year beginning on 1 August of the year prior to the identified year in the x-axis.

As shown above, the major wet period of the 1997-98 ENSO event had a considerable impact generating the most extreme events. However, the next ten 5-year periods with the most events were all *prior to 1998* and none since. There is no trend toward increasing incidence of heavy 5-day periods (also true for 3-day, 14-day and 30-day) and thus it is clear evidence that

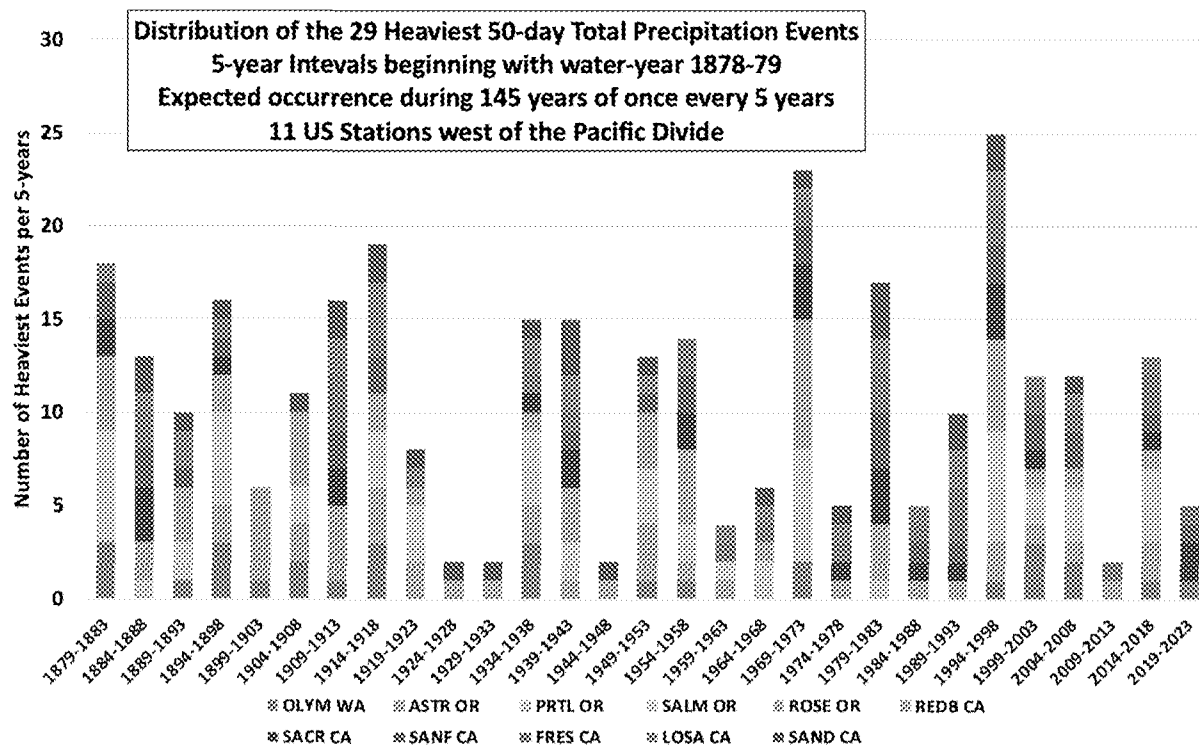
does not support the claims made in 3OD which include the claim that AR events are getting wetter (p. 2-12).

The recent 50-day period (1 Dec 2022 to 19 Jan 2023) was characterized by a series of AR events impinging on the West Coast. The following chart again breaks down the time distribution of the 26 heaviest 50-day events in the past 130 years (if random, once every five years on average).



JRC Fig. 4 As in Fig. 3 but for 50-day precipitation totals.

Further, regarding AR events, we have 11 stations which began records by 1878 and thus we can examine a longer period of 145 years (i.e. 1878-79 to 2022-23). Again, there is no indication that there has been an increase in rainfall due to a sequence of AR events JRC Fig. 5



NOAA/NCEI data updated 23 Jan 2023
 John R. Christy, The University of Alabama in Huntsville

JRC Fig. 5. As in Fig. 3 but starting with the 1878-79 water-year.

It should be noted that for the one station with observations back to 1849 (San Francisco), the wettest 50-day period was during the so-called “Ark-storm” of 1861-62 with 32.43 inches and 1997-98 was 2nd at 25.22 inches. Interestingly 1877-78 (just outside of JRC Fig. 5) was 3rd with 23.86 inches. Then 2023 at 20.49 inches was 4th, representing only 74% of the record amount. This information indicates choosing the last 40 to 70 years for the sample size of determining changes, as the 3OD does, misleads the public to conclusions that are falsifiable when longer periods are examined.

Daily precipitation for 27 long-term stations in Minnesota from 1892-2021 (a state within the area alleged to have increases of 45% since 1958 in heavy rainfall events; 3OD Fig. 2.7) shows the decade with most of the heavy 3-day events was 1892-1901. Also, for extreme heavy events (6 inches in 5 days) these stations experienced 35 events in the 20 years of 1892-1911 vs. 40 events in 2002-2021, or little difference. As expected, periods in the 1910s and 1930s experienced a dearth of events. The evidence does show a tendency for more of the heaviest events to have occurred recently in MN, but much less than indicated rise in 3OD Fig. 2.7. (Charts not shown, but available on request – the effort to build complete daily precipitation datasets are tedious and to date I only have MN in the upper Midwest finished.). The information for the SE US, as published in McKittrick and Christy 2019, demonstrates directly

that the alleged 37% increase in 3OD Fig. 2.7 is not reproduceable when utilizing the entire period of record (b. 1872) or even for periods beginning more recently.

Droughts*****

3OD p 2-15 bottom and 2-16 droughts. When discussing paleo records this section is a clear example of misinformation, i.e. ignoring evidence to that contradicts the claim. One of the clearest examples of this is the use of the paper by Williams et al. 2022 who picked “22 years” as the sample size for their analysis. Why 22-years? Because if the period were longer, say, 25-years or more, the statistics would fail since heavy rainfall years of 1998 and earlier would negate the significance. And, the current wet year 2022-23, if included, will put a damper on the statistics as well. If such a paper is cited in the NCA, it will be demonstrated (again) that the NCA document is misleading the public. See <https://cliffmass.blogspot.com/2022/02/is-southwest-us-experiencing.html> by Prof. Cliff Mass of UW for refutation of Williams et al. with observational evidence.

Please include the studies that demonstrate past drought episodes were far longer and drier as demonstrated, for example, by 600 to 1200-year-old tree trunks which grew to maturity on dry ground but today which are well below the surface of current natural lakes in the Sierra Nevada mountains. (see Lindstrom 1990, Morgan and Pomerleau 2012,). This is inarguable evidence that the southwestern droughts of the last millennium were much drier and intense than any today regardless of what Williams et al. claim. Not including this contradictory evidence again places strain on the notion that the NCA5 is a credible document.

Example of unsupported claim (one of many) that is sermonizing*****

“Key Message 2.3. The Future is in our hands”

As demonstrated above, extreme events are not confidently related to GHG emissions and, as demonstrated, do not pose a threat (see below for our current lack of understanding about the physical climate system.) Without an understanding of natural variability, or as this document assumes, natural variability is unimportant and not consequential, such sermonizing here might represent the sentiment of the authors, but it cannot stand up to scientific cross-examination.

As I have demonstrated before the US Congress (without rebuttal), if the United States ceased to exist today, the GHG impact on the climate system would be essentially imperceptible by 2100 (about 0.1 C if models are useful). So, Key Message 2.3 is not true, the climate “Future” is not in our (US) hands. However, the consequence of making energy less affordable and inaccessible is very clear and dangerous to humankind. So, yes, the “Future [OF HUMAN THRIVEABILITY] is in Our Hands” and we should support the expansion of affordable energy into the lives of those much less fortunate than us (who are the rich few) so they too can experience longer and better lives. I lived in Africa and can say with all confidence - without energy, life is brutal and short. If the NCA5 is going to allow sermons, then people with alternate views based on real evidence should be given a chance to preach.

30D Fig. 2.9. Precipitation changes

Models are incapable of predicting precipitation changes. As noted in Christy and McNider 2016, the models failed to replicate variability and trends for both temperature and precipitation in Alabama. Similarly, for Minnesota, simple annual averages of precipitation varied from 400 mm to 950 mm per year relative to an observational mean of 660 mm. This wide range represents major errors in the moist thermodynamics of the models related to latent heat and moisture convergence (not shown but available on request.). At the very least, the authors should place error bars on the grid-point values of precipitation changes and I suspect most will cross “zero change”.

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John R. Christy
The University of Alabama in Huntsville
27 January 2023

Comments on NCA5 Third Order Draft (3OD)

Chapter 3

Climate drivers*****

As I've indicated earlier, knowing the "why" of climate change is far more uncertain than this document suggests. NCA 3OD Fig. 3.1 (a reconstruction of IPCC AR6 Fig. 3.8) demonstrates this lack of understanding. Firstly, the aerosol-cooling "driver" in models is not well-known. The impact of aerosols computed as a temperature change over the past 100+ years in the CMIP-6 models (from AR6 Fig. 3.8) range from -1.0 to +0.1°C. This represents a *200% range of uncertainty in the response relative to the median value*, and even then it is not known if the actual value is within this range. This is a metric that is not directly measurable and so is essentially guestimated. Thus, this easily demonstrates, using AR6 (and NCA5) information that the "why" due to the aerosol "driver" is not well-known as claimed.

The uncertainty of the GHG "driver" (response) over the past 100+ years is similarly murky. The models range in response from +1.0 to +2.2°C – *a range of uncertainty of over 1°C, or 65% of the median*. As AR6 Fig. 3.8 shows, even by significant "tuning" the models (see below on tuning), many fall outside of the target temperature range (which was known ahead of time, so there should be no surprise that many models came close). Thus, it is easy to demonstrate from AR6 (and NCA5) that the "why" due to GHG "driver" is not well-known as claimed.

CAUSES OF WARMING 1850-1900 to 2010-2019

Final Government Distribution

Chapter 3

IPCC AR6 WG1

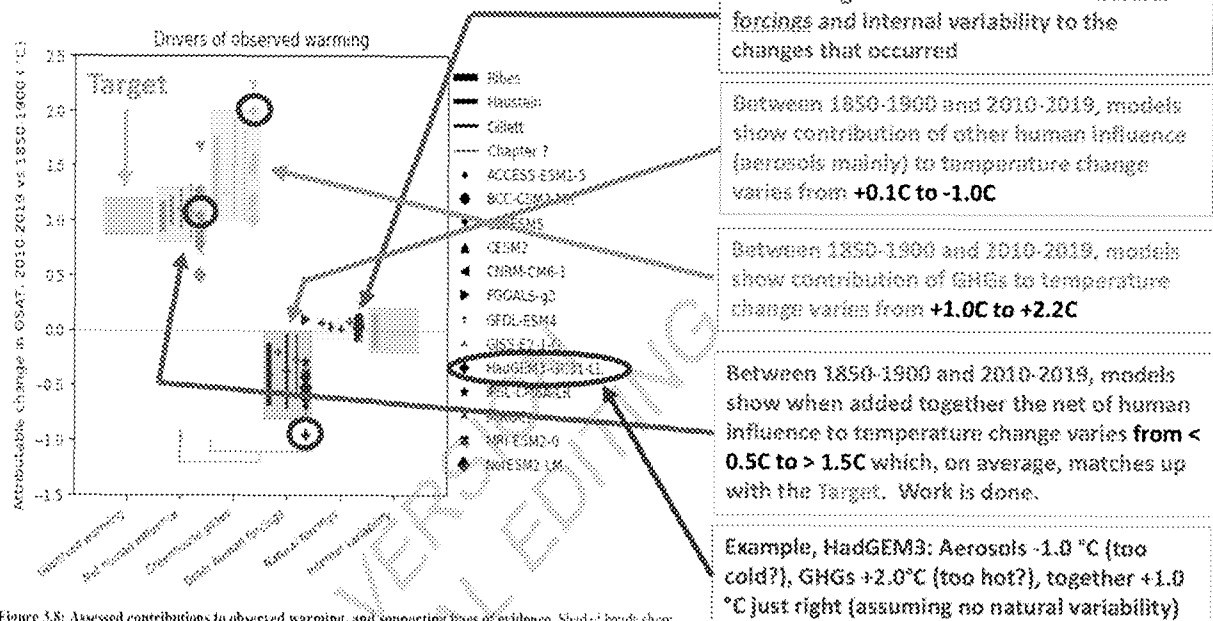


Figure 3.8: Assessed contributions to observed warming, and supporting lines of evidence. Shaded bands show assessed likely ranges of temperature change in GSAI, 2010-2019 relative to 1850-1900, attributable to natural human influence, well-mixed greenhouse gases, other human forcings (aerosols, ozone, and land-use).

Because models are tuned to surface temperature they can tune (adjust) the impact of various forcing mechanisms as needed to get the right answer in the end – the physics are not known (i.e. understanding is low) as can be seen by the varying impacts of GHGs (+1.0 to +2.2°C), and Aerosols (-1.0 to +0.1°C) among the models. So, the modeler concludes (with hubris) that since natural factors sum to zero in nature, humans must have caused all of the warming since the 19th century.

JRC Fig 6. Copy of Fig. 3.8 IPCC AR6 with annotations that explain the diagram and text.

One clear example of the scientific uncertainty is found in the highly regarded HadGEM3-OC31-LL model. This model's aerosol "driver" equates to -1.0 °C (too cold?), but its GHG "driver" is +2.0 °C (too hot?) which when added together, lands the outcome at +1.0 °C ("just right"). The models have such wide ranges in the response to the "drivers" that the conclusion must be there are significant uncertainties in how the aerosols and GHGs impact the climate system, not to mention the physical thermodynamical/dynamical processes. This is clear evidence that "scientists" do not understand "why" the climate system behaves as it does very well at all.

Regarding the "tuning" claim above, this fact was best said by the author of another highly-regarded model, the MPI-ESM1.2, T. Mauritsen.

We have documented how we tuned the MPI-ESM1.2 global climate model to match the instrumental record warming; an endeavor which has clearly been successful. Due to the historical order of events, the choice was to do this practically by targeting an ECS of about 3 K using cloud feedbacks, as opposed to tuning the aerosol forcing. (Mauritsen and Roeckner 2020 "Tuning the MPI-

ESM1.2 global climate model to improve the match with instrumental record warming by lowering its climate sensitivity. Epdf/10.1029/2019MS002037).

As Mauritsen and Roeckner explain, most of their model parameterizations were already fixed in code when their initial, poor result was computed. So, to produce the desired outcome, they tinkered with the cloud-feedback parameterization to force the model to produce a pre-determined outcome. The reader is left to determine whether this represents scientific certainty ... or something else, and this clear statement of tuning should be included in the NCA5 to inform the reader of the problems with models.

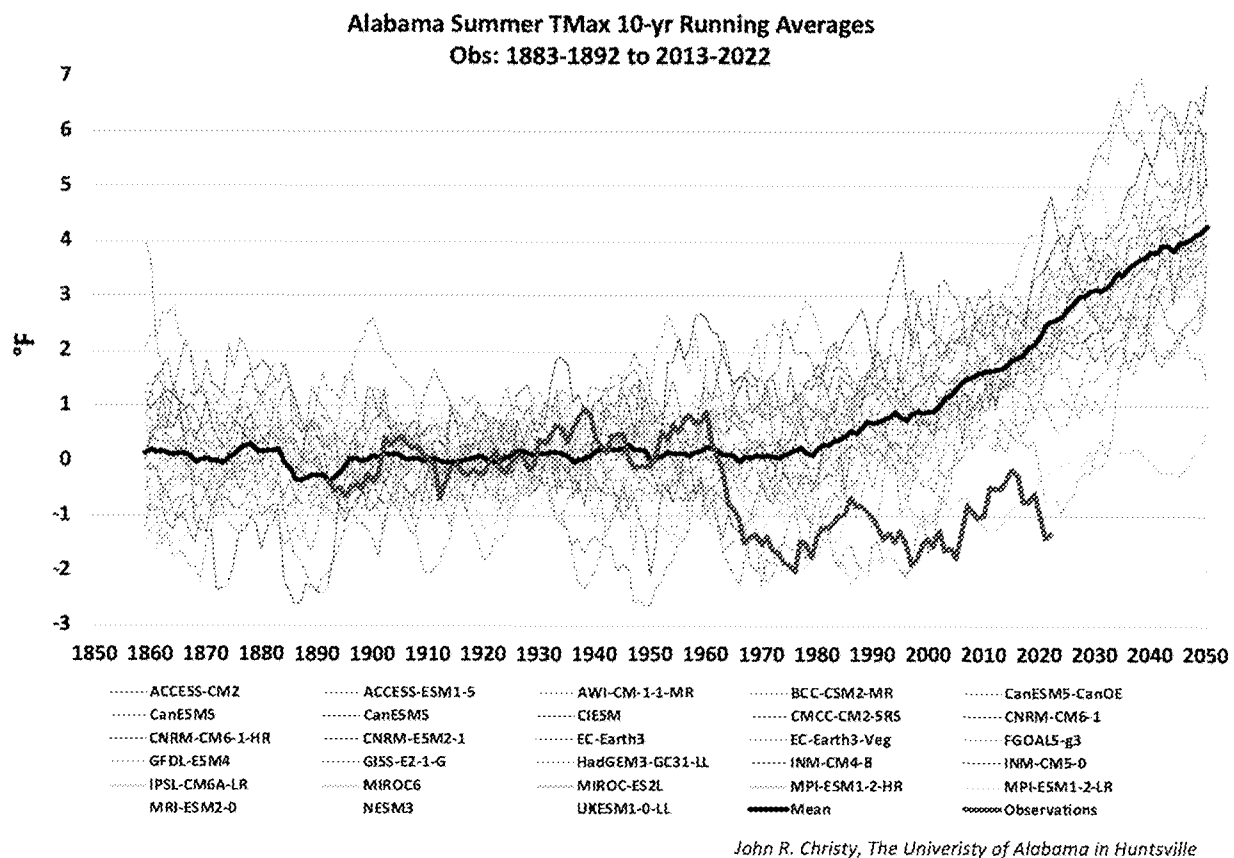
The 3OD then makes the claim based on a study performed by many IPCC AR6 Lead Authors (Sherwood et al. 2020) that the Equilibrium Climate Sensitivity is likely between +2.5°C and +4.0°C. This in itself betrays some of the uncertainty in climate science as the range is fairly wide. However, the NCA5 has misled the readers by ignoring a major critique of the Sherwood et al. study on which the IPCC relied.

Lewis 2022 (Climate Dynamics, but a layman's explanation can be found here <https://judithcurry.com/2022/09/20/important-new-paper-challenges-ipccs-claims-about-climate-sensitivity/>) determined that the ECS range was estimated to be 1.75 to 2.7°C, with the possible lower bound being even smaller. Lewis discovered that Sherwood et al made significant errors, was inconsistent and used an outdated input of one of the key drivers. Sherwood et al. also ignored published articles that calculated lower ECS values than they concluded. In other words, Lewis's more thoroughly-documented range of ECS values is essentially outside (lower than) that of the AR6 (and NCA5) claim. In the NCA5 3OD draft (downloaded on 20 Jan 2023), there was no mention of this critically important paper and to ignore its profound and contradictory findings will not accrue confidence in the NCA5 nor its authors. At the least, Lewis demonstrates the lack of understanding of the climate system and the "drivers" that affect it and at the most indicates the very basis for the climate alarm promoted in 3OD is unjustified.

Related to this is (again) the lack of reference to scientific information that contradicts the storyline of this section. McKittrick and Christy (2020) demonstrated that all of the climate models used in the IPCC AR6 overestimated the tropospheric temperature change. This paper received the notoriety of being one of the top ten downloaded papers in this AGU journal. Similarly, Mitchell et al. 2020 also documented the "persistent model biases" that challenge the notion that models actually represent the real climate system to a degree needed to determine the response of a forcing perturbation (extra GHGs) that represent less than 1 percent of the energy flows. Science requires the testing of claims, and there is much evidence to demonstrate that the claims made in NCA5 about model prowess are improperly and misleadingly made. Thus, predictions about the future should be assigned very low confidence since the models could not even reproduce the past 40 years as documented in McKittrick and Christy (2020) and Mitchell et al. (2020) among other studies.

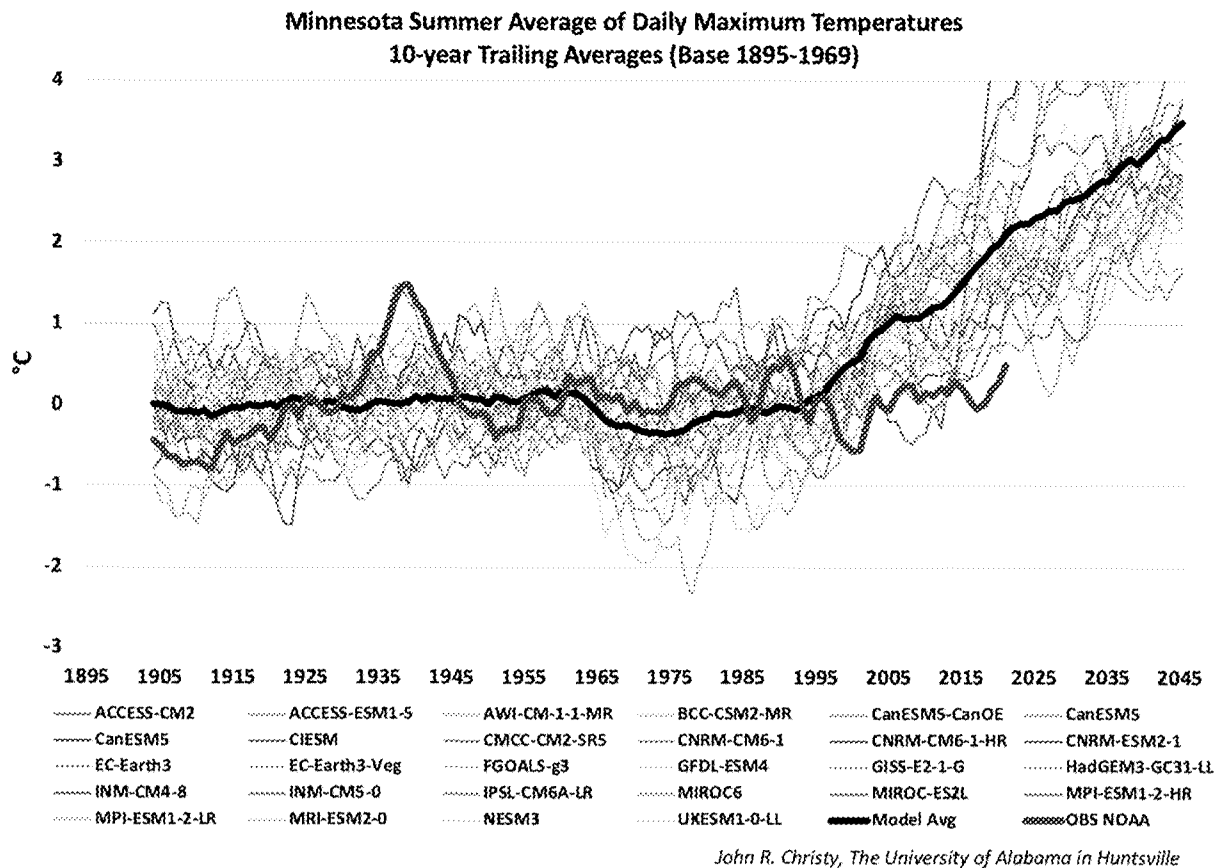
Why is the tropospheric temperature important? The climate is a system of interdependent components, and unless the complete system is modeled correctly, the model fails. It is one thing to tune a particular parameter to force it to agree with observations, it's quite another to model a system that faithfully represents all of the major and interdependent components. Indeed, the tropical troposphere in particular is a critical component to reproduce accurately because this is where the major flows of heat occur and where the response to GHGs should be the most readily observed. Models fail in this.

On a more local level, I show two examples of models' inability to produce actual observations over the period of enhanced GHG forcing. The first, JRC Fig. 7, was published in Christy 2022 "A Practical Guide to Climate Change in Alabama." This result was previously published in Christy and McNider (J. Clim App Meteor 2016) using CMIP-5 models and here updated with CMIP-6 model output. The conclusion of the 2016 study, and which applies to this comparison with CMIP-6 models was, "Seventy-seven CMIP5 climate model runs are examined for Alabama and indicate no skill at replicating long-term temperature or precipitation changes since 1895." Indeed, as seen below, the average model has predicted over 2°C more warming that actually occurred in the state for summertime maximum temperatures.



JRC Fig. 7. Comparison between 28 CMIP-6 model runs and observations (red) as 10-year running averages for JJA TMax in Alabama.

A second similar example has been computed for the state of Minnesota.



JRC Fig. 8. As in JRC Fig. 7 but for Minnesota.

The models all show warming responses at a point when, in the models, the GHGs began to perceptibly “drive” the climate around 1995. This response is not found in the observations. Indeed, the temperature in the upper Midwest has shown no change in the last 80 years (and a decline if starting in the dust-bowl 1930s). These two charts demonstrate that our theoretical understanding of changes in regional surface temperatures are not complete enough to even reproduce what has already happened and thus should not be used for projections as the models are already well off the mark.

Why June/July/August TMax as a metric? There are many reasons, with the first being the fact that the basic survivability of flora and fauna are generally constrained by the extremes of the environment. Summertime is the hottest season of course, so any additional warming here would indicate a potential problem for the ecosystem. Secondly, summer temperatures have a lower magnitude of interannual variability and so any signal of change in the background climate should be easier to detect. Thirdly, the value of the daytime TMax is less affected by the growth of infrastructure around the station (unlike nighttime TMin) as the daytime heating

generates atmospheric motions which mix the air over a large scale and thus allows for a more representative measure of the temperature. TMin occurs in the decoupled nocturnal boundary layer that is highly influenced by changes in the local surroundings and represents a very shallow layer of air (Christy et al. 2009 and references therein). Finally, many early stations were agricultural stations which operated only during the growing season, usually April to October.

There are numerous other issues I have seen in the 3OD but this is all the time I can allow to address what I think are fundamental, systemic problems with the models on which the 3OD relied and which have not been communicated to the reader.

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John R. Christy
The University of Alabama in Huntsville
27 January 2023

Comments on NCA5 Third Order Draft (3OD)

Basic issues

At the present, this NCA report reads as a set of claims about the climate that are intended to support a political agenda. The general failure of the report is found in the following issues, examples of which will follow in the appropriate chapters 2 and 3.

1. Pervasive neglect of information that qualifies or contradicts the claims being made
 - a. Selecting specific time periods which mislead regarding true variability
2. Overstatement of confidence in our understanding of the climate system
 - a. Understatement of significant uncertainties with climate model results
 - b. Neglect of information that demonstrates climate model failings
 - c. Use of virtually impossible emission scenarios
3. Understatement or dismissal of the role of natural variability in climate variations
4. Sermonizing about policy directions

Many of NCA5 claims are often unscientific, especially in the sense the 3OD does not provide information that mitigates or even contradicts the claims being made. Political documents don't offer negative views to their claims but addressing such counter-claims is a bedrock of science. I realize my effort to influence the report is a fool's errand as my review of the ZOD (which was based on reproducible, published information) was ignored. But I hope someone with an objective mind will read and understand the implications of this submission. If these issues aren't addressed, this information will be made public in unknown ways and thus reduce any credibility that one might attach to the report.

Since the entire report depends on two basic assertions;

1. Chapter 2: Climate is changing for the worse due to humans
2. Chapter 3: Models are reliable as predictors,

I will stay mostly in those two areas. Showing the problems with these two thrusts will then reduce or eliminate the alarm generated by all of the succeeding chapters. I refer to sections in the draft with the symbol "3OD" and for my own products as "JRC".

(a sideline) 3OD Chapter 1

3OD Fig. 1.4 The claims of the billion-dollar losses has been analytically criticized by Roger Pielke Jr., arguably the most published person on this topic, as one of the poorest examples of

analysis or “climate misinformation” designed to alarm the reader rather than inform them. Please read here <https://rogerpielkejr.substack.com/p/billion-dollar-disasters-are-a-national>

“The billion-dollar disaster tally is easy to understand, simple to communicate, but in actual fact, incredibly misleading. It is climate misinformation.”

On Jun 22, 2025, at 11:47 AM, Cohen, Seth <seth.cohen@hq.doe.gov> wrote:

Privileged & Confidential
.....

I worry that taking a step towards publicity will center this team in the policy debate, rather than the science. Further, I fear that publishing an article about your work on a government committee will raise questions about how the report came to fruition, tainting your efforts to remain apolitical.

As drafted, your dual reports deliver clean, fatal blows to NCA5. I see no additional benefit from a policy piece, only controversy.

Best regards,

SMC

From: Judith Curry <curry.judith@gmail.com>

Sent: Sunday, June 22, 2025 12:08 PM

To: Steven Koonin <steven.koonin@gmail.com>

Cc: Roy Spencer <roywspencer@hotmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; John Christy <climatemanager60@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Josh Loucks <loucksj14@gmail.com>; Cohen, Seth <seth.cohen@hq.doe.gov>

Subject: [EXTERNAL] Re: write a policy piece?

Interesting idea

We should also think about op-eds, blog posts for circa Jul 13

On Sun, Jun 22, 2025 at 8:29 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Should we collectively author a policy piece to be submitted to, say, Science mag's Policy Forum.

<https://www.science.org/action/doSearch?AllField=policy+forum>

It could be titled something like "Reflections on the National Climate Assessment"

Would they dare publish it? Since our critique will have the status of an official USG document, that might help.

If not Science, then perhaps we could try Issues in Science and Technology?

Steve Koonin

--

<~WRD0000.jpg>

Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

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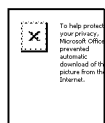
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Steve Koonin

From: John Christy <climateman60@gmail.com>
Sent: Monday, August 25, 2025 1:31 PM
To: Ross McKitrick
Cc: Ison, Jeremy T.; Judith Curry; Roy W. Spencer; Steven Koonin
Subject: Re: Public comments compilation

Agree - it's laborious to check each comment when they are not organized in any sensible way.

Has anyone heard of the call today? I'm headed off to class soon and will be out of touch until 5p ET. I haven't heard the call has been postponed.

John C.

On Mon, Aug 25, 2025 at 11:17 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:

I spent a few hours unsuccessfully trying to get Grok and Copilot to generate R scripts to download the published comments into a spreadsheet. As near as I can figure the website renders them in Java and the R packages I can use can't seem to read them.

Is it possible on the DoE side to dump the comments into a spreadsheet that shows the name of the commenter and the comment itself on each row? I can work with the from there.

This will make dealing with them much easier and help with the preparation of the response record.

From: Ross McKittrick <ross.mckitrick@gmail.com>
Sent: Monday, August 25, 2025 12:17 PM
To: Ison, Jeremy T.; Judith Curry; John Christy; Roy W. Spencer; Steven Koonin
Subject: Public comments compilation

I spent a few hours unsuccessfully trying to get Grok and Copilot to generate R scripts to download the published comments into a spreadsheet. As near as I can figure the website renders them in Java and the R packages I can use can't seem to read them.

Is it possible on the DoE side to dump the comments into a spreadsheet that shows the name of the commenter and the comment itself on each row? I can work with the from there.

This will make dealing with them much easier and help with the preparation of the response record.

From: John Christy <climateman60@gmail.com>
Sent: Tuesday, May 6, 2025 3:48 PM
To: Steve Koonin
Cc: Travis Fisher; Ross McKittrick; Judith Curry; Roy W. Spencer
Subject: Re: Virtual meeting with the Secretary

Travis

2p ET is 8a Honolulu time ... so I should be good with that time.

Buddy Menton would be a great reviewer.

Another is Matthew Wielicki - has Earth Science skills (PhD geology), lots of climate knowledge and will be honest if he sees flaws in our reasoning.

I'm assuming this first review is to help us avoid missing important studies as well as to cross the I's and dot the T's. I would think that in the "Author's Prefix" Steve would say something like "Hey, give us a break ... we had only 7 weeks from our first meeting on 11 April. We may have missed something ... we'll fix it later".

John C.

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville
climateman60@gmail.com

On May 6, 2025, at 1:57 PM, Steven Koonin <steven.koonin@gmail.com> wrote:

The virtual meeting times work for me.

On potential reviewers, I'm OK with the list. But as someone else noted, it's a bit of an echo chamber. in my own work I've found it valuable to have some knowledgeable non-experts weigh in. Here are a few people who are literate, careful readers, and who I'm quite sure would keep a confidence:

- Mark Mills and/or Scott Tinker
- Francis (Buddy) Menton

SEK

From: Travis Fisher <travis.scott.fisher@gmail.com>
Sent: Tuesday, May 6, 2025 12:52 PM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: Ross McKittrick <ross.mckittrick@gmail.com>; Judith Curry <curry.judith@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>
Subject: Virtual meeting with the Secretary

Hi all,

You seem to be cooking with gas, as they say, so I'll keep this update short.

First, I'm hoping to squeeze us all in for a virtual meeting or phone call with the Secretary this Thursday afternoon. The time would likely be 2 pm to 2:30 pm ET, but we should keep some flexibility on the earlier end (try to keep your calendars clear from 1:15 pm to 2:30 pm ET). Feel free to come with questions for the Secretary, and if there's anything I can try to answer beforehand, please let me know.

Second, if we put together a rapid review team, who would you all feel comfortable including? Below my signature, I have a list of the names I've heard so far. My suggestion would be to either keep this group small or only solicit their input once the first draft is published--we have to weigh the benefit of external review against the risk of a leak. We have some flexibility in whether or how we do any review, so let me know if you have any strong preferences.

Best,
Travis

Possible review team

Roger Pielke Jr.
Cliff Mass
Will Happer
Richard Lindzen
Nick Lewis (UK)
Ryan Maue
Kevin Dayaratna

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Tuesday, May 6, 2025 2:58 PM
To: 'Travis Fisher'
Cc: 'Ross McKitrick'; 'Judith Curry'; 'John Christy'; 'Roy W. Spencer'
Subject: RE: Virtual meeting with the Secretary

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Sent: Tuesday, May 6, 2025 12:52 PM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: Ross McKitrick <ross.mckitrick@gmail.com>; Judith Curry <curry.judith@gmail.com>; John Christy <climatemanager60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>
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Travis

Possible review team

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Cliff Mass
Will Happer

Richard Lindzen
Nick Lewis (UK)
Ryan Maue
Kevin Dayaratna

From: Roy Spencer <roywspencer@hotmail.com>
Sent: Tuesday, May 6, 2025 1:51 PM
To: Travis Fisher; Steven Koonin
Cc: Ross McKittrick; Judith Curry; John Christy
Subject: Re: Virtual meeting with the Secretary

I don't have any objections to any of those names... But keep in mind a few of them will want (more of) their publications to be referenced and/or additional points made. ;-)
-Roy

From: Travis Fisher <travis.scott.fisher@gmail.com>
Sent: Tuesday, May 6, 2025 11:52 AM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: Ross McKittrick <ross.mckittrick@gmail.com>; Judith Curry <curry.judith@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>
Subject: Virtual meeting with the Secretary

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Cliff Mass
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Nick Lewis (UK)
Ryan Maue
Kevin Dayaratna

From: Judith Curry <curry.judith@gmail.com>
Sent: Tuesday, May 6, 2025 1:31 PM
To: Travis Fisher
Cc: Steven Koonin; Ross McKittrick; John Christy; Roy W. Spencer
Subject: Re: Virtual meeting with the Secretary

This time works for me

Re reviewers, I don't think these reviewers (if their names are made public) would help the credibility of our report; looks too much like pal review (and several of them have a narrow range of relevant expertise). They might have some useful suggestions, but it will be too late for structural changes to the report

I think the second more substantive document (to be finished later in 2025) should go out for a serious review, where the reviews and our responses are published.

On Tue, May 6, 2025 at 9:52 AM Travis Fisher <travis.scott.fisher@gmail.com> wrote:
Hi all,

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First, I'm hoping to squeeze us all in for a virtual meeting or phone call with the Secretary this Thursday afternoon. The time would likely be 2 pm to 2:30 pm ET, but we should keep some flexibility on the earlier end (try to keep your calendars clear from 1:15 pm to 2:30 pm ET). Feel free to come with questions for the Secretary, and if there's anything I can try to answer beforehand, please let me know.

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Roger Pielke Jr.
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Nick Lewis (UK)
Ryan Maue
Kevin Dayaratna

--



To help protect
your privacy,
Microsoft Office
prevented
automatic
download of this
picture from the
Internet.

Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

From: Travis Fisher <travis.scott.fisher@gmail.com>
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Best,
Travis

Possible review team

Roger Pielke Jr.
Cliff Mass
Will Happer
Richard Lindzen
Nick Lewis (UK)
Ryan Maue
Kevin Dayaratna

From: Roy Spencer <roywspencer@hotmail.com>
Sent: Tuesday, April 15, 2025 5:31 PM
To: John Christy
Subject: RE: [4.3]Apr15[JC] CO2 impact on global climate

Ok, thanks.

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: John Christy <climateman60@gmail.com>
Date: 4/15/25 4:29 PM (GMT-06:00)
To: Ross McKittrick <ross.mckittrick@gmail.com>, Roy Spencer <roywspencer@hotmail.com>, Steve Koonin <steven.koonin@gmail.com>
Subject: [4.3]Apr15[JC] CO2 impact on global climate

Roy

I see you have section 4.3. Attached is a short background on the vehicle thing with calculations I did for the Vermont Trial (which eventually led to the vehicle rules and the EF) and my work on the EPA SAB vehicle rule before I was canned.

John C.

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Wednesday, May 21, 2025 4:35 PM
To: 'Roy Spencer'; 'Judith Curry'; 'Ross McKittrick'; 'John Christy'
Subject: AI executive summary

FYI, here's what MS Copilot offered when I asked it to distill the current executive summary into 1 page of text.

Not too bad, but with some flubs.

I'll try some other LLMs and send around a more serious draft by Friday.

SEK

This report examines the role of carbon dioxide (CO₂) in environmental and climate dynamics, evaluating its direct impacts, human influences, climate sensitivity, model reliability, extreme weather trends, sea level changes, attribution challenges, agricultural effects, risk management, economic considerations, and policy implications.

CO₂, unlike Criteria Air Contaminants, does not directly affect air quality or human health at ambient levels but is significant due to its role in climate change. It enhances plant growth through photosynthesis and global greening, though its absorption in seawater can impact ocean alkalinity and coral ecosystems. Human activities contribute to climate variability, with CO₂ emissions altering radiative balance, while solar influences remain debated. Climate projections often overestimate warming, and extreme emission scenarios, such as RCP8.5, are now considered implausible.

Climate models consistently show warming biases, producing excessive surface, tropospheric, and stratospheric temperature changes. Most types of extreme weather show no statistically significant long-term trends, though hot days in the U.S. have increased since the 1950s. U.S. wildfire activity remains influenced by forest management. Sea level rise has varied regionally, with highest increases linked to land subsidence rather than climate effects.

Attribution of climate change impacts remains uncertain due to high natural variability, measurement limitations, and reliance on models with deficiencies. Climate sensitivity estimates from observational data are lower than model-generated values, with the IPCC adjusting sensitivity ranges in its latest reports. While CO₂-induced warming may bring benefits to agriculture, such as increased crop productivity and improved adaptation, concerns over negative impacts are often unsubstantiated.

Extreme weather-related losses are largely driven by economic and population growth, with improved forecasting and infrastructure mitigating risks. The social cost of carbon (SCC) remains highly uncertain, reflecting broad assumptions about economic and climate interactions. U.S. emissions policies are expected to have negligible direct effects on global climate, with any impact materializing over long time frames.

This report highlights the complexities of climate science and policy, emphasizing the need for rigorous analysis, careful attribution, and realistic projections.

Steve Koonin

From: John Christy <climateman60@gmail.com>
Sent: Monday, August 11, 2025 11:25 AM
To: Ross McKittrick; Judith Curry; Roy Spencer; Steve Koonin; Jeremy T. Ison
Subject: Re: Expert Reviewers

All

We have a mistake on page 90 first bullet. Arctic Sea Ice Extent - the link is to the Southern Hemisphere which shows a tiny decline, the link to the Arctic (change the "s" to an "n" in the link) shows 20 percent decline. This was pointed out by one of Cliff Mass's angry colleagues whom I will thank and ask to please put it in the public comments.

Arctic:
https://nsidc.org/data/seaice_index/images/n_plot_hires.png

Antarctic:
https://nsidc.org/data/seaice_index/images/s_plot_hires.png

John C.

On Wed, Aug 6, 2025 at 9:52 AM John Christy <climateman60@gmail.com> wrote:
All

I spoke with Cliff Mass who said he would be happy to be an expert reviewer. He's an elected Councillor of the AMS, is very well known and thus has creds.

I know Lindzen has a skeptic's baggage (as most of us do) but often has some clever insights in how to explain climate issues.

I haven't seen the most recent list of reviewer suggestions. Judy, could you send the list as a response to this email so we have a thread with a subject line dealing only with expert reviewers?

Thanks

John C.

From: John Christy <climateman60@gmail.com>
Sent: Wednesday, August 6, 2025 10:53 AM
To: Ross McKittrick; Judith Curry; Roy Spencer; Steve Koonin; Joshua Loucks; Cohen, Seth; Park, Charles; Travis Fisher
Subject: Expert Reviewers

All

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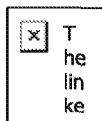
Thanks

John C.

From: Judith Curry [curry.judith@gmail.com]
Sent: 6/9/2025 10:48:30 PM
To: Steven Koonin [steven.koonin@gmail.com]
CC: John Christy [climateman60@gmail.com]; Ross McKittrick [ross.mckittrick@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; Josh Loucks [loucksj14@gmail.com]
Subject: overconfidence
Attachments: Overconfidence when stating conclusions.docx

see attached text for overconfidence. I moved the hurricane example here. Could use some more examples

--



Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
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Overconfidence when stating conclusions

The NCA5 uses specific terms to convey information about scientific confidence associated with important finds, observations and projections. The Front Matter of the NCA5 states that “confidence in a finding is based on the type, amount, quality, strength, and consistency of evidence; the skill, range, and consistency of methods to detect, evaluate, attribute, and interpret climate trends; and the degree of agreement across scientific information sources.”

Table 1 provides calibrated language for confidence assessment:

Very high:	Strong evidence (established theory, multiple sources, well documented and accepted methods, etc.). High consensus
High:	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.). Medium consensus
Medium:	Suggestive evidence (a few sources, limited consistency, methods emerging, etc.) Competing schools of thought.
Low:	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.). Disagreement or lack of opinions among experts.

This terminology is inflated: *high confidence* with just moderate evidence and medium consensus; *medium confidence* with only suggested evidence and competing schools of thought. This inflation in terminology leads to overconfidence in the conclusions.

Even within the context of this inflated terminology, NCA5 further inflates the confidence level of many of its conclusions to well beyond what the IPCC has concluded with more thorough justification, and also by incorrectly applying its own standards. Several illustrative examples are provided.

Key Message 3.1 Traceable Account states: “There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have unequivocally caused *all* global warming observed over the industrial era.” Compare the NCA5 statement with statements from the IPCC AR5 and AR6:

AR5: “It is *extremely likely* that *more than half* of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together.” (IPCC, 2013)

AR6: “The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is

very likely that well-mixed GHGs were the main driver of tropospheric warming since 1979.” (IPCC, 2021)

The IPCC AR5 and AR6 statements provide likelihood assessments but not a confidence level. While the NCA5 claims with *very high confidence* that fossil fuels have unequivocally caused *all* global warming, the AR5 refers to “*more than half* of the observed warming” and the AR6 provides a more nuanced statement that relates to a *likely* range of warming contributed to by human drivers.

NCA5 Key message 2.2: “Hurricanes have been intensifying more rapidly since the 1980s (*high confidence*) and causing heavier rainfall and higher storm surges (*high confidence*).” No justification is provided in Chapter 2 for the *high confidence* conclusion on higher storm surges or hurricanes causing heavier precipitation. The Traceable Accounts section, Description of Confidence and Likelihood states: “Basic physical understanding and climate models both provide robust explanations for the links between climate change and observed changes in these extremes: this is why the authors also have *high confidence* that storms are delivering more rainfall and high confidence that storm surges are becoming higher.” In short, the NCA5 provides no observational basis or published research for their *high confidence* assertions that hurricanes are causing heavier rainfall and higher storm surges; and does not meet its own standards for a *high confidence level*.

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Sunday, August 10, 2025 12:57 PM
To: Ross McKittrick; Roy W. Spencer; John Christy; Judith Curry; Travis Fisher
Subject: RPjr talking about CWG25

A Jeffries podcast worth listening to if you've not already done so.

https://players.brightcove.net/4090876629001/default__default/index.html?videoId=6376636130112

Steven E. Koonin

From: John Christy <climateman60@gmail.com>
Sent: Wednesday, June 18, 2025 9:56 AM
To: Ross McKittrick
Cc: Judith Curry; Seth Cohen; Joshua Loucks; Travis Fisher; Steve Koonin; roywspencer@hotmail.com
Subject: Re: CWG report metadata

Ross

Yes. Same dataset for both.

John C.

Sent from my iPhone

On Jun 18, 2025, at 5:21 AM, Ross McKittrick <ross.mckitrick@gmail.com> wrote:

Hi John

I had no trouble accessing the data. I'll add the reference. Was this the archive used for both reports?

On Tue, Jun 17, 2025 at 8:38 PM John Christy <climateman60@gmail.com> wrote:
Ross

See if you can access this directory. I have a readme file, station list and the two main datafile set for public access.

This provides all of the ushcn daily surface temperature data used in my charts.

https://www.nsstc.uah.edu/data/ushcn_jrc/

John C.

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville
climateman60@gmail.com

On Jun 16, 2025, at 10:01 AM, Ross McKittrick <ross.mckittrick@gmail.com> wrote:

I've gone through Judy's excellent metadata listing. I added in Steve's notes. The ones I could resolve I did, the others are indicated with the relevant name in red before each one (John or Roy at this point).

For Ch 5 rather than renumber every figure I changed the figure number in the box to Figure 5.1; now everything follows in order.

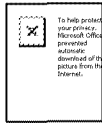
John for the list in Sect. 6.3 and 6.4 if you can get the spreadsheets to me I can post them in an archive then add the DOI where needed.

On Fri, Jun 13, 2025 at 2:07 PM Judith Curry <curry.judith@gmail.com> wrote:
I've taken a first cut at an Appendix on Metadata.

Some ancillary things I've spotted (for Ross):
No figure 5.1 (chapter figs need renumbering)
Figure 6B.1 is misnumbered (should be 5B.1)
Missing ref for LIZUNDIA LOIOLA in ch 6

Several things for SK, see
Fig 2.2
Fig 6B.1
Fig 7.6

Many things for RM, JC, RS; maybe ross can take a first cut through these



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<Metadata.[RM June16].docx>

From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Wednesday, June 18, 2025 9:21 AM
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Cc: Judith Curry; Cohen, Seth; Loucks, Joshua; Fisher, Travis; Steve Koonin; roywspencer@hotmail.com
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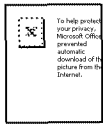
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<Metadata.[RM June16].docx>

From: Steven Koonin [steven.koonin@gmail.com]
Sent: 6/18/2025 11:13:37 AM
To: 'John Christy' [climateman60@gmail.com]; 'Ross McKittrick' [ross.mckitrick@gmail.com]
CC: 'Judith Curry' [curry.judith@gmail.com]; 'Cohen, Seth' [seth.cohen@hq.doe.gov]; 'Loucks, Joshua' [Joshua.Loucks@hq.doe.gov]; 'Fisher, Travis' [travis.fisher@hq.doe.gov]; roywspencer@hotmail.com
Subject: RE: CWG report metadata
Attachments: ~WRD0001.jpg

I was able to access, although I didn't try to download the large data files.

SEK

From: John Christy <climateman60@gmail.com>
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Cc: Judith Curry <curry.judith@gmail.com>; Cohen, Seth <seth.cohen@hq.doe.gov>; Loucks, Joshua <Joshua.Loucks@hq.doe.gov>; Fisher, Travis <travis.fisher@hq.doe.gov>; Steve Koonin <steven.koonin@gmail.com>; roywspencer@hotmail.com
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Missing ref for LIZUNDIA LOIOLA in ch 6

Several things for SK, see

Fig 2.2

Fig 6B.1

Fig 7.6

Many things for RM, JC, RS; maybe ross can take a first cut through these

Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

<Metadata.[RM June16].docx>

From: John Christy <climateman60@gmail.com>
Sent: Tuesday, June 17, 2025 8:38 PM
To: Ross McKittrick
Cc: Judith Curry; Cohen, Seth; Loucks, Joshua; Fisher, Travis; Steve Koonin; roywspencer@hotmail.com
Subject: Re: CWG report metadata

Ross

See if you can access this directory. I have a readme file, station list and the two main datafile set for public access.

This provides all of the ushcn daily surface temperature data used in my charts.

https://www.nsstc.uah.edu/data/ushcn_jrc/

John C.

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville
climateman60@gmail.com

On Jun 16, 2025, at 10:01 AM, Ross McKittrick <ross.mckittrick@gmail.com> wrote:

I've gone through Judy's excellent metadata listing. I added in Steve's notes. The ones I could resolve I did, the others are indicated with the relevant name in red before each one (John or Roy at this point).

For Ch 5 rather than renumber every figure I changed the figure number in the box to Figure 5.1; now everything follows in order.

John for the list in Sect. 6.3 and 6.4 if you can get the spreadsheets to me I can post them in an archive then add the DOI where needed.

On Fri, Jun 13, 2025 at 2:07 PM Judith Curry <curry.judith@gmail.com> wrote:

I've taken a first cut at an Appendix on Metadata.

Some ancillary things I've spotted (for Ross):
No figure 5.1 (chapter figs need renumbering)
Figure 6B.1 is misnumbered (should be 5B.1)

Missing ref for LIZUNDIA LOIOLA in ch 6

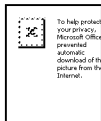
Several things for SK, see

Fig 2.2

Fig 6B.1

Fig 7.6

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<Metadata.[RM June16].docx>

From: John Christy <climateman60@gmail.com>
Sent: Monday, June 16, 2025 11:32 AM
To: Ross McKittrick
Cc: Judith Curry; Seth Cohen; Joshua Loucks; Travis Fisher; steven.koonin@gmail.com; roywspencer@hotmail.com
Subject: Re: CWG report metadata

Ross

... between Fairbanks and Denali at the moment. I'll try to get something to you tonight. I'm 4 hours behind EDT.

John C.

Sent from my iPhone

On Jun 16, 2025, at 7:01 AM, Ross McKittrick <ross.mckittrick@gmail.com> wrote:

I've gone through Judy's excellent metadata listing. I added in Steve's notes. The ones I could resolve I did, the others are indicated with the relevant name in red before each one (John or Roy at this point).

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<Metadata.[RM June16].docx>

From: Ross McKittrick [ross.mckittrick@gmail.com]
Sent: 6/16/2025 3:01:16 PM
To: Judith Curry [curry.judith@gmail.com]
CC: Cohen, Seth [seth.cohen@hq.doe.gov]; Loucks, Joshua [Joshua.Loucks@hq.doe.gov]; Fisher, Travis [travis.fisher@hq.doe.gov]; climateman60@gmail.com; steven.koonin@gmail.com; roywspencer@hotmail.com
Subject: Re: CWG report metadata
Attachments: Metadata.[RM June16].docx

I've gone through Judy's excellent metadata listing. I added in Steve's notes. The ones I could resolve I did, the others are indicated with the relevant name in red before each one (John or Roy at this point).

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Figure 6B.1 is misnumbered (should be 5B.1)

Missing ref for LIZUNDIA LOIOLA in ch 6

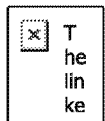
Several things for SK, see

Fig 2.2

Fig 6B.1

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Appendix: Metadata for Figures, Tables

Figure 2.1 Screen shot from Figure 3 of Zhu et al. 2016

<https://www.nature.com/articles/nclimate3004>

Figure 2.2 Data replotted from Berner 2006 Figure 18, with annotation in red added by authors

<https://www.sciencedirect.com/science/article/pii/S0016703706002031>

Figure 2.3 Screen shot from Gerhart and Ward (2010) Figure 2

<https://nph.onlinelibrary.wiley.com/doi/pdf/10.1111/j.1469-8137.2010.03441.x>

Figure 2.4 Screenshot from Copernicus Marine Services

[https://data.marine.copernicus.eu/product/GLOBAL OMI HEALTH carbon ph area averaged/description](https://data.marine.copernicus.eu/product/GLOBAL_OMI_HEALTH_carbon_ph_area_averaged/description)

Figure 2.5 Screen shot from AIMS (2023) Figures 2-4

[https://www.aims.gov.au/sites/default/files/2022-08/AIMS LTMP Report on%20GBR coral status 2021 2022 040822F3.pdf](https://www.aims.gov.au/sites/default/files/2022-08/AIMS_LTMP_Report_on%20GBR_coral_status_2021_2022_040822F3.pdf)

Figure 3.1.1 Screen shot of AR6 WG1 Ch2 Fig 10

Figure 3.1.2 Screen shot of AR6 WG1 Ch7 Fig 7-6

Figure 3.1.3 Author created figure. CO2 data source:

<https://gml.noaa.gov/ccgg/trends/index.html>

Figure 3.2.1 Screen shot from Hausfather et al. (2019) Figure S4

<https://doi.org/10.1029/2019GL085378>

ROY Figure 3.2.2 Author created figure. Data source: Freidlingstein et al. (2024) LINK TO ACTUAL DATA???

<https://essd.copernicus.org/preprints/essd-2024-519>

ROY Figure 3.2.3 Screen shot from Friedlingstein 2024 Figure number? CANT FIND THE FIGURE IS THIS AUTHOR CREATED? IF SO, NEED SPECIFIC LINK TO THE DATA [RM] Also need to add in if trends are OLS or something else.

ROY Figure 3.2.4 Screen shot from Friedlingstein 2024 Figure number? CANT FIND THE FIGURE IS THIS AUTHOR CREATED? IF SO, NEED SPECIFIC LINK TO THE DATA [RM] Also need to add in if trends are OLS or something else.

Figure 4.1 Screen shot from Scafetta (2021) Figure 1

<https://doi.org/10.3390/cli9110161>

ROY Figure 6B.1 (misnumbered.) Author created figure. Data source: <https://climexp.knmi.nl/start.cgi> NEED DETAILS ON METHOD

Figure 5.1 NOTE: NO NUMBER 5.1

Figure 5.2 Screen shot from Scafetta (2023) Figure 2
<https://doi.org/10.1007/s00382-022-06493-w>

ROY Figure 5.3 Author created figure, updated from Spencer (2024) IN WHAT WAY? REFERENCE TO A SPECIFIC FIGURE? [RM] Also need to add in if trends are OLS or something else.
<https://www.heritage.org/environment/report/global-warming-observations-vs-climate-models>

Figure 5.4 Author created figure, based on Figure 3 of McKittrick and Christy (2020)
<https://doi.org/10.1029/2020EA001281>
Updated using same methods and data extended from 2014 to 2024, see McKittrick and Christy (2025) in chapter references.

Figure 5.6 Screen shot of IPCC AR5 Figure 10.SM1, with author annotations

JOHN Figure 5.7 Author created figure following Christy and McNider (2017) with updated data
DESCRIBE DIFFERENCES, SOURCES OF DATA
<https://doi.org/10.1007/s13143-017-0070-z>

Figure 5.8 Screen shot from
https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhland&ui_season=1
(accessed May 27, 2025)

Figure 5.9 Screen shot from Rugenstein and Hakuba (2023) Figure 1
<https://doi.org/10.1029/2022GL101802>

ROY Figure 5.10 Author created figure DETAILS

Figure 6.1.1 Author replot of Figure 10 from Koutsoyiannis (2013) F
<http://dx.doi.org/10.1080/02626667.2013.804626>

Figure 6.2.1 Screen shot of figure from Maue (2025)
<https://climatlas.com/tropical/>

Figure 6.2.2 Author created figure. Data from National Hurricane Center (2024)
<https://www.nhc.noaa.gov/climo/>

Figure 6.2.3 Author created figure. Data from NOAA HRD
https://www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html

Table 6.2.1 Author created table. Data from NOAA HRD
https://www.aoml.noaa.gov/hrd/hurdat/most_intense.html

Figure 6.3.1 Screen shot from NCA4 Figure 6.4

JOHN Figure 6.3.2 ~~IS THIS SCREEN SHOT OR AUTHOR CREATED~~. Source: USHCN

JOHN Figure 6.3.3 Author created figure. ~~Data source, methods~~

JOHN Figure 6.3.4 Author created figure. Data source: USHCN data ~~methods~~

JOHN Figure 6.3.4 Author created figure. Data source: USHCN data ~~methods~~

JOHN Figure 6.3.6 Author created figure. Data source: USHCN data ~~methods~~

Figure 6.3.7 Screen shot from <https://www.globalchange.gov/indicators/heat-waves>

~~Figure 6.3.8 Author created figure. DATA SOURCE~~

JOHN Box tables. Author created table ~~DATA SOURCE~~

JOHN Figure 6.4.2 Author created figure ~~DATA SOURCE~~

JOHN Figure 6.4.3 Author created figure ~~DATA SOURCE~~

JOHN Figure 6.4.4 Author created figure ~~DATA SOURCE~~

JOHN Figure 6.4.5 Author created figure ~~DATA SOURCE~~

Figure 6.5.1 Author created figure. Data source: [https://www.spc.noaa.gov/wcm/data/1950-2024 actual tornadoes.csv](https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv)

Figure 6.7.1 Author created figure. Data source:
<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0> accessed June 16, 2025. OLS trend line added.

Figure 6.8.1 Screen shot from Lizundia-Loiola *et al.* (2021) Figure 12.

Figure 6.8.2 Screenshot from Marlon et al. (2012) Figure 2 panel C.
<https://www.pnas.org/doi/pdf/10.1073/pnas.1112839109>

Figure 6.8.3 Author created Figure. Data 1926 to 2016:
https://web.archive.org/web/20200212033452/https://www.nifc.gov/fireInfo/fireInfo_stats_tot

alFires.html. Post-2017 <https://www.nifc.gov/fire-information/statistics/wildfires> Accessed June 16, 2025.

Figure 7.1 Screenshot from <https://tidesandcurrents.noaa.gov/sltrends/>

Table 7.1 Author created table. From Section 6.2 of <https://judithcurry.com/wp-content/uploads/2018/11/special-report-sea-level-rise-3.pdf>

Figure 7.2 Screenshot from https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290 (downloaded 4/22/25)

Figure 7.3 Screenshot from https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8771450 (downloaded 4/22/2025)

Figure 7.4 Screenshot from https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8761724 (downloaded 4/22/25)

Figure 7.5 Screenshot from https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750 (downloaded 4/22/25)

Figure 7.6 Author created figure. Data from https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750

Figure 8.1 Screenshot from <https://crudata.uea.ac.uk/cru/data/temperature/HadCRUT5.0Analysis.pdf>

Figure 8.2 Screenshot from Hansen and Karecha (2025) Figure 1 <https://www.columbia.edu/~jeh1/mailings/2025/CloudFeedback.13May2025.pdf>

Table 8.1 Screenshot of column 1 of Table 12.12 IPCC AR6 Working Group I report

Figure 9.1 Screenshot From Taylor and Schlenker (2021) Figure 1 <https://www.nber.org/papers/w29320>

Figure 9.2 Screenshot from McKittrick (2025) Figure 1 <https://www.nature.com/articles/s41598-025-90254-2>

Figure 10.1 Screenshot from Pielke (2024) <https://www.nature.com/articles/s44304-024-00011-0> Figure 3.

Figure 10.2 Screenshot from Gasparini et al. (2015) Figure 2
[http://dx.doi.org/10.1016/S0140-6736\(14\)62114-0](http://dx.doi.org/10.1016/S0140-6736(14)62114-0)

Figure 11.1 Screen shot from Pielke Jr (2023)
<https://rogerpielkejr.substack.com/p/global-disaster-losses1990-2023>

Figure 11.2 Screenshot from CEA-OMB (2023) <https://bidenwhitehouse.archives.gov/wp-content/uploads/2023/03/CEA-OMB-White-Paper.pdf> Figure 1.

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Friday, June 13, 2025 2:27 PM
To: 'Judith Curry'; 'Cohen, Seth'
Cc: 'Loucks, Joshua'; 'Fisher, Travis'; climateman60@gmail.com; ross.mckitrick@gmail.com; roywspencer@hotmail.com
Subject: RE: CWG report metadata
Attachments: ~WRD0003.jpg

Fig 2.2: My reconstructed plot of data from the GEOCARBIII trace of Figure 18 of Berner (2006):

Berner, R.A. (2006) GEOCARBSULF: A combined model for Phanerozoic atmospheric O₂ and CO₂. *Geochimica et Cosmochimica Acta* 70 (2006) 5653–5664. <https://www.sciencedirect.com/science/article/pii/S0016703706002031>

Fig 6B.1: That's Roy's figure

Fig 7.6: Figure caption describes what's plotted (i.e., 30-yr trailing trends). Data source is NOAA data for the Battery: https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750

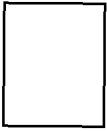
From: Judith Curry <curry.judith@gmail.com>
Sent: Friday, June 13, 2025 2:07 PM
To: Cohen, Seth <seth.cohen@hq.doe.gov>
Cc: Loucks, Joshua <Joshua.Loucks@hq.doe.gov>; Fisher, Travis <travis.fisher@hq.doe.gov>; climateman60@gmail.com; ross.mckitrick@gmail.com; steven.koonin@gmail.com; roywspencer@hotmail.com
Subject: CWG report metadata

I've taken a first cut at an Appendix on Metadata.

Some ancillary things I've spotted (for Ross):
No figure 5.1 (chapter figs need renumbering)
Figure 6B.1 is misnumbered (should be 5B.1)
Missing ref for LIZUNDIA LOIOLA in ch 6

Several things for SK, see
Fig 2.2
Fig 6B.1
Fig 7.6

Many things for RM, JC, RS; maybe ross can take a first cut through these



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To: Judith Curry
Cc: Cohen, Seth; Loucks, Joshua; Fisher, Travis; climateman60@gmail.com; steven.koonin@gmail.com; roywspencer@hotmail.com
Subject: Re: CWG report metadata

Just heading to Chicago for the weekend for a family visit. I'll get on this Monday AM.

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Subject: CWG report metadata
Attachments: Metadata.docx

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Appendix: Metadata for Figures, Tables

Figure 2.1 Screen shot from Figure 3 of Zhu et al. 2016

<https://www.nature.com/articles/nclimate3004>

Figure 2.2 Screen shot of Berner 2006, with annotation in red added by authors

CHECKED THE PAPER. STEVE DID YOU CREATE THIS FIGURE, HOW WAS THE DATA MADE AVAILABLE

<https://www.sciencedirect.com/science/article/pii/S0016703706002031>

Figure 2.3 Screen shot from Gerhart and Ward (2010) Figure 2

<https://nph.onlinelibrary.wiley.com/doi/pdf/10.1111/j.1469-8137.2010.03441.x>

Figure 2.4 Screenshot from Copernicus Marie Services

https://data.marine.copernicus.eu/product/GLOBAL_OMI_HEALTH_carbon_ph_area_averaged/description

Figure 2.5 Screen shot from AIMS (2023) Figures 2-4

https://www.aims.gov.au/sites/default/files/2022-08/AIMS_LTMP_Report_on%20GBR_coral_status_2021_2022_040822F3.pdf

Figure 3.1.1 Screen shot of AR6 WG1 Ch2 Fig 10

Figure 3.1.2 Screen shot of AR6 WG1 Ch7 Fig 7-6

Figure 3.1.3 Author created figure. CO2 data source:

<https://gml.noaa.gov/ccgg/trends/index.html>

Figure 3.2.1 Screen shot from Hausfather et al. (2019) Figure S4

<https://doi.org/10.1029/2019GL085378>

Figure 3.2.2 Author created figure. Data source: Freidlingstein et al. (2024) LINK TO ACTUAL DATA???

<https://essd.copernicus.org/preprints/essd-2024-519>

Figure 3.2.3 Screen shot from Friedlingstein 2024 Figure number? CANT FIND THE FIGURE IS THIS AUTHOR CREATED? IF SO, NEED SPECIFIC LINK TO THE DATA

Figure 3.2.4 Screen shot from Friedlingstein 2024 Figure number? CANT FIND THE FIGURE IS THIS AUTHOR CREATED? IF SO, NEED SPECIFIC LINK TO THE DATA

Figure 4.1 Screen shot from Scafetta (2021) Figure 1

<https://doi.org/10.3390/cli9110161>

Figure 6B.1 (misnumbered.) Author created figure. Data source: <https://climexp.knmi.nl/start.cgi> NEED DETAILS ON METHOD

Figure 5.1 NOTE: NO NUMBER 5.1

Figure 5.2 Screen shot from Scafetta (2023) Figure 2
<https://doi.org/10.1007/s00382-022-06493-w>

Figure 5.3 Author created figure, updated from Spencer (2024) IN WHAT WAY? REFERENCE TO A SPECIFIC FIGURE?
<https://www.heritage.org/environment/report/global-warming-observations-vs-climate-models>

Figure 5.4 Author created figure, based on Figure 3 of McKittrick and Christy (2020) UPDATED HOW?
<https://doi.org/10.1029/2020EA001281>

Figure 5.6 Screen shot of IPCC AR5 Figure 10.SM1, with author annotations

Figure 5.7 Author created figure following Christy and McNider (2017) with updated data DESCRIBE DIFFERENCES, SOURCES OF DATA
<https://doi.org/10.1007/s13143-017-0070-z>

Figure 5.8 Screen shot from
https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhland&ui_season=1 (accessed May 27, 2025)

Figure 5.9 Screen shot from Rugenstein and Hakuba (2023) Figure 1
<https://doi.org/10.1029/2022GL101802>

Figure 5.10 Author created figure DETAILS

Figure 6.1.1 Author replot of Figure 10 from Koutsoyiannis (2013) F
<http://dx.doi.org/10.1080/02626667.2013.804626>

Figure 6.2.1 Screen shot of figure from Maue (2025)
<https://climatlas.com/tropical/>

Figure 6.2.2 Author created figure. Data from National Hurricane Center (2024)
<https://www.nhc.noaa.gov/climo/>

Figure 6.2.3 Author created figure. Data from NOAA HRD
https://www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html

Table 6.2.1 Author created table. Data from NOAA HRD

https://www.aoml.noaa.gov/hrd/hurdat/most_intense.html

Figure 6.3.1 Screen shot from NCA4 Figure 6.4

Figure 6.3.2 IS THIS SCREEN SHOT OR AUTHOR CREATED. Source: USHCN

Figure 6.3.3 Author created figure. Data source, methods

Figure 6.3.4 Author created figure. Data source: USHCN data methods

Figure 6.3.4 Author created figure. Data source: USHCN data methods

Figure 6.3.6 Author created figure. Data source: USHCN data methods

Figure 6.3.7 Screen shot from <https://www.globalchange.gov/indicators/heat-waves>

Figure 6.3.8 Author created figure. DATA SOURCE

Box tables. Author created table DATA SOURCE

Figure 6.4.2 Author created figure DATA SOURCE

Figure 6.4.3 Author created figure DATA SOURCE

Figure 6.4.4 Author created figure DATA SOURCE

Figure 6.4.5 Author created figure DATA SOURCE

Figure 6.5.1 Author created figure. Data source: [https://www.spc.noaa.gov/wcm/data/1950-2024 actual tornadoes.csv](https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv)

Figure 6.7.1 Author created figure. Data source:
<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0> METHOD

Figure 6.8.1 Screen shot from Lizundia-Loiola *et al.* (2021) Figure number
REFERENCE TO LIZUNDIA LOIOLA IS MISSING

Figure 6.8.2 Screenshot from Marlon et al. (2012) I CANT FIND THE FIGURE
<https://www.pnas.org/doi/pdf/10.1073/pnas.1112839109>

Figure 6.8.3 Screenshot from NEED BETTER SOURCE, WEB LINK

Figure 7.1 Screenshot from <https://tidesandcurrents.noaa.gov/sltrends/>

Table 7.1 Author created table. From Section 6.2 of
<https://judithcurry.com/wp-content/uploads/2018/11/special-report-sea-level-rise-3.pdf>

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Figure 7.3 Screenshot from
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Figure 7.4 Screenshot from
https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8761724 (downloaded 4/22/25)

Figure 7.5 Screenshot from
https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750 (downloaded 4/22/25)

Figure 7.6 Author created figure. Data from SK
NEED A SPECIFIC LINK AT TIDES AND CURRENTS

Figure 8.1 Screenshot from
<https://crudata.uea.ac.uk/cru/data/temperature/HadCRUT5.0Analysis.pdf>

Figure 8.2 Screenshot from Hansen and Karecha (2025) Figure 1
<https://www.columbia.edu/~jeh1/mailings/2025/CloudFeedback.13May2025.pdf>

Table 8.1 Screenshot of column 1 of Table 12.12 IPCC AR6 Working Group I report

Figure 9.1 Screenshot From Taylor and Schlenker (2021) Figure 1
<https://www.nber.org/papers/w29320>

Figure 9.2 Screenshot from McKittrick (2025) Figure 1
<https://www.nature.com/articles/s41598-025-90254-2>

Figure 10.1 Screenshot from Pielke (2024) NEED LINK OR SOMETHING, THIS REF ISN'T IN
PIELKE 2024

Figure 10.2 Screenshot from Gasparini et al. (2015) Figure 2
[http://dx.doi.org/10.1016/S0140-6736\(14\)62114-0](http://dx.doi.org/10.1016/S0140-6736(14)62114-0)

Figure 11.1 Screen shot from Pielke Jr (2023)
<https://rogerpielkejr.substack.com/p/global-disaster-losses1990-2023>

Figure 11.2 Screenshot from CEA-OMB (2023) NO REFERENCE

From: Travis Fisher <travis.scott.fisher@gmail.com>
Sent: Wednesday, June 11, 2025 11:26 AM
To: Ross McKitrick
Cc: Steven Koonin; John Christy; Josh Loucks; seth.cohen@hq.doe.gov; Judith Curry; Roy Spencer
Subject: Re: Meeting

I suggest a quick meeting at 9 am ET on Friday. If we know for sure there's no news to share, we can cancel it (but I have a hunch there will be news).

Sorry to misread your availability, Ross. My fault.

On Wed, Jun 11, 2025 at 11:18 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:
I can do Friday early morning. But unless there's news from the higher-ups that needs immediate response I also think we could wait until next week.

On Wed, Jun 11, 2025 at 11:12 AM Steven Koonin <steven.koonin@gmail.com> wrote:

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We'll be en route to Chicago after 11:30am on Friday so I won't be able to make the call. Do we have a set of topics to be covered? If there are important updates perhaps Travis can update me separately next week.

Ross

On Tue, Jun 10, 2025 at 9:51 AM John Christy <climateman60@gmail.com> wrote:

Tavis

I'll be in the Atlanta airport 12:20p to 1:50p ET and perhaps able to connect. If I'm the kink, most of my work in terms of building datasets is done at this point, so no real loss with my absence. I have a few more word-choice-questions to ask later today.

John C.

On Mon, Jun 9, 2025 at 9:41 PM Travis Fisher <travis.scott.fisher@gmail.com> wrote:

Ok, it looks like we'll lose someone at just about any time this week.

John, if we meet at noon ET on Friday, will you be able to join?

What works best for you, Judy?

On Mon, Jun 9, 2025 at 4:03 PM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

I'm free this week except:

Wednesday 11:15 to 1 PM EDT

Thursday 8:30 to 10:00 AM

Friday 11:30 onwards

On Mon, Jun 9, 2025 at 3:52 PM Steven Koonin <steven.koonin@gmail.com> wrote:

Can't do Tuesday at 2 pm. But free any other time that day except 1330-1430.

Wednesday is good except 1200-1300 and 1500-1630.

Thursday doesn't work at all (at LLNL)

Friday I can make work anytime, but 1300-1500 wouldn't be optimal.

[All times above are EDT]

SEK

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To: seth.cohen@hq.doe.gov; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Judith Curry <curry.judith@gmail.com>; Roy Spencer <roywspencer@hotmail.com>; John Christy <climateman60@gmail.com>

Subject: Meeting

Hi Everyone,

I wanted to put together another meeting/chat to help organize and keep everyone on the same page.

I know we discussed Tuesday on the call previously, but Wednesday could also work.

Would Tuesday at 2:00 pm EST work for everyone?

Please let me know if another time is better for everyone.

Thanks! - Josh

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Sent: Friday, August 1, 2025 2:52 PM
To: Roy Spencer
Cc: Ross McKittrick; Steven Koonin; Judith Curry; Josh Loucks; Seth Cohen; Travis Fisher
Subject: Re: NCA5 Review TX Floods

All

Cliff Mass has forwarded to me several emails from incensed colleagues at UW who claim we don't know how the radiation budget works, the IPCC was misrepresented etc. I told Cliff to tell those folks to write out their complaints and send them via the portal.

As to records ... funny how they change when you have more data. I recall a reporter who wrote a story about Huntsville weather after I had added 50 years of data - saying, "Huntsvilles records just got hotter, colder wetter and drier"

See you in a minute.

John C.

On Fri, Aug 1, 2025 at 1:41 PM Roy Spencer <roywspencer@hotmail.com> wrote:
Judy just finished a very nice podcast with Heartland. I learned a couple of things.
-Roy

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> I have shown the July 1900 observer's report and Roy's graph of the heaviest 2-day events in two separate presentations this week

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>> On Jul 28, 2025, at 12:29, John Christy <climateman60@gmail.com> wrote:

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>> I'm putting the finishing touches on a dataset of 21 stations in Flash Flood Alley (TX) starting in 1893. Data are difficult to find and some forms have never been keyed into computer-readable files, including daily data from the Cotton Region Stations. I'm working on Kerrville today (just down river from Mystic Camp) for data prior to the regular station reports that began in 1902. I ran across this for July 1900 (attached) in which a rain total of 11.60" fell on the 15th and the observer remarked about it.

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>> Note he says the river rose 33 ft. Recall the river rose 25ft at Kerrville in the recent July 4th flood. There is already ample evidence that bad floods happen here, but this is an example of data not keyed-in our NOAA official files that can provide better evidence to determine the likelihood of extreme events.

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>> In any case, we can use the results of our (i.e. Ross's) analyses of these 21 stations in our review of NCA5 to give an example of what an NCA should be doing to understand and prepare for natural variability vs. climate change (and how pathetic the information was in NCA5.)

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>> p.s. Recall that two months later in Sept 1900, the worst hurricane death toll in US history occurred in Galveston. It was a bad year for Central TX.

>> <414780_190007_Kerrville.pdf>

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You busy man.

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Sent: Friday, August 1, 2025 1:07 PM
To: John Christy <climateman60@gmail.com>
Cc: Ross McKittrick <ross.mckittrick@gmail.com>; Judith Curry <curry.judith@gmail.com>; Roy Spencer <roywspencer@hotmail.com>; Steve Koonin <steven.koonin@gmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>; Travis Fisher <travis.fisher@hq.doe.gov>
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From: Ross McKittrick [ross.mckittrick@gmail.com]
Sent: 8/1/2025 6:22:40 PM
To: Steven Koonin [steven.koonin@gmail.com]
CC: John Christy [climateman60@gmail.com]; Judith Curry [curry.judith@gmail.com]; Roy Spencer [roywspencer@hotmail.com]; Josh Loucks [loucksj14@gmail.com]; Seth Cohen [seth.cohen@hq.doe.gov]; Travis Fisher [travis.fisher@hq.doe.gov]
Subject: Re: NCA5 Review TX Floods
Attachments: Malinina and Gillett-PNW heatwave.pdf

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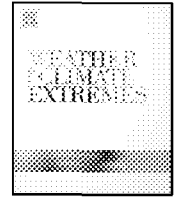
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The 2021 heatwave was less rare in Western Canada than previously thought

Elizaveta Malinina^{*}, Nathan P. Gillett

Canadian Centre for Climate Modelling and Analysis (CCCma), Environment and Climate Change Canada (ECCC), 2474 Arbutus Rd., Victoria (BC), Canada V8N 1V8

ARTICLE INFO

Dataset link: [era5cll](#), [ECCC data portal](#), [GIGab](#)

Keywords:

Pacific Northwest heatwave
Attribution
Canada
CMIP6
ERA5

ABSTRACT

The 2021 Pacific Northwest heatwave resulted in record temperatures observed across the Canadian provinces of British Columbia, Alberta and Saskatchewan as well as the US states of Washington and Oregon. Previous studies of extreme temperatures over arbitrarily-defined rectangular regions covering parts of Oregon, Washington and British Columbia have estimated return periods of 200–100 000 years, generally based on data since 1950, with some analyses suggesting that the event would have been considered impossible based on statistical fits to pre-2021 data, or based on climate models failing to simulate such events. We estimate a return period of 1152 (126– ∞) years for the 2021 event averaged over British Columbia, based on a generalized extreme value distribution (GEV) with a location parameter a function of global mean surface temperature fitted to 1950–2021 ERA5 data. British Columbia was the province where the highest absolute temperature of 49.6 °C was measured, and where the largest impacts on human mortality and ecosystems were reported. However, we show that this return period is reduced to 236 (52– ∞) years when the analysis period is extended back to 1940, using newly-available ERA5 data, owing to an extreme heatwave observed in 1941. While the 1941 event was 1.7 °C cooler than the 2021 event in British Columbia, it was a rarer event relative to the cooler climatology of the time, with an estimated return period of 735 (135– ∞) years. Over this longer period we also find that almost all CMIP6 models underestimate variability in annual maximum temperatures over British Columbia. The return period of the 1941 heatwave was comparable to that of the 2021 event in Alberta and Saskatchewan, though not in Washington or Oregon. While the 2021 event was an unprecedented and extremely intense heatwave whose likelihood was much increased by human-induced climate change, our results indicate that this event was not as rare as previously thought in Western Canada.

1. Introduction

In late June 2021 temperatures of almost 50 °C were observed in British Columbia, Canada (e.g. Philip et al., 2022). New Canadian temperature records were set three days in a row in the village of Lytton in Southern British Columbia (BC) from 27 to 29 June 2021 (ECCC Weather BC, 2021a,b), with the maximum of 49.6 °C recorded on the 29th of June (WMO, 2021), exceeding pre-2021 record (45.0 °C observed in 1937 in Yellowgrass, SK) by almost 5 °C. Although British Columbia was the hotspot, it was not the only place where record high temperatures were observed. Washington (WA) state, to the south of British Columbia, as well as its southern neighbour Oregon (OR) also experienced record-high temperatures (Philip et al., 2022), as did parts of Alberta (AB) and Saskatchewan (SK) (White et al., 2023).

The extreme heat resulted in a substantial death toll in the region. BC Coroners Service (2022) stated that in the Province of British Columbia 619 deaths were associated with the extreme heat in the period from 25 June to 2 July 2021, and in Washington State 100

deaths were attributed to the heat (Washington State Department of Health, 2021). Additionally, there were reports of extensive damage to marine and terrestrial ecosystems (e.g. Raymond et al., 2022; Sloane et al., 2022).

Because the heatwave was so impactful, in the first year after the heatwave there were several studies which looked at several aspects of the event, including its return period and how much likely it was made by anthropogenic climate change. Most of these studies have focused on TXx (annual maxima of daily maximum temperature) in a rectangular region between 45–52° N and 119–123° W covering parts of British Columbia, Washington and Oregon (Philip et al., 2022; Thompson et al., 2022), or more extensive rectangular regions (McKinnon and Simpson, 2022; Bartussek et al., 2022). In addition to the rectangular region, Thompson et al. (2022) provided analysis of the event rarity in terms of standard deviation using regions from Stone (2019), though their return period analysis was done using the same rectangular region as Philip et al. (2022). While Philip et al. (2022) stress that their

^{*} Corresponding author.

E-mail address: elizaveta.malinina-rieger@ec.gc.ca (E. Malinina).

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choice of region was guided by the event's impacts rather than its meteorological extremity, there is nonetheless a danger of selection bias effects associated with the choice of such regions a posteriori (Miralles and Davison, 2023).

Previous studies of the event have used a range of methods to estimate the event's return period from observations. Philip et al. (2022) applied a non-stationary GEV (generalized extreme value) fit to ERA5 over the period 1950–2021, with a location parameter dependent on global mean surface temperature (GMST), and concluded that the event was approximately a 1 in 1000 year event. They also found that a similar fit using 1950–2020 data indicated that an event of the magnitude of the 2021 event was virtually impossible (Philip et al., 2022). Similarly, Thompson et al. (2022) investigated the level of extremity of the event over the same region using ERA5 and JRA55 reanalysis data since 1950. The authors found that the 2021 Western North American heatwave was a 3.6 standard deviation event relative to the surrounding two week period based on 1950–2020 ERA5 data, and was one of the most extreme events recorded globally in terms of standard deviations from climatological values. Bartusek et al. (2022) fitted a non-stationary GEV distribution to ERA5 TXx over a larger region that includes AB and most of BC, and found that the return period of the 2021 event was much larger than 1000 years based on a fit to 1950–2020 data, and about 200 years based on a fit to the 1950–2021 data.

McKinnon and Simpson (2022) examined the rareness of the 2021 heatwave event by looking at the skewness and kurtosis of the maximum temperature at weather stations in the region between 43° N and 57° N and between 115° W and 123° W. They calculated the rareness of the event by comparing the maximum daily temperature in 2021 with the standard deviation of TXx over prior years with varying record lengths across stations. They then examined the CESM2 large ensemble and found that 4.5 standard deviation anomalies comparable to those observed, were approximately 1 in 100 000-yr events in the model.

A number of studies have used either comparisons of single or multi-model large ensembles to estimate risk ratios for the event in the current climate versus the preindustrial climate, finding risk ratios ranging from of least 150 (Philip et al., 2022) to at least 500 000 (Bartusek et al., 2022), as well as to derive projected changes in the frequency of such events under future climate change (Philip et al., 2022; Thompson et al., 2022; Bartusek et al., 2022). Such findings are typically very sensitive to the simulation of realistic variability of such extremes. The other techniques include use initialized simulations to estimate risk ratios or human-induced changes in the intensity of such events (e.g. Bercoff-Hickey et al., 2022) as well as climate model simulations which are initialized with minimal perturbations in the initial conditions to determine if the models can simulate the events of that magnitude (so-called ensemble boosting) (Fischer et al., 2023).

Several studies have examined the synoptic and meteorological reasons for the strength of heatwave (Neal et al., 2022; Lin et al., 2022; Bartusek et al., 2022). The general consensus is that there was a very strong blocking over the region, which allowed the warm air from the low latitudes to penetrate deep to the North (Mo et al., 2022). It has also been suggested that changes in soil moisture contributed to the strength of the observed temperatures (Philip et al., 2022; Bartusek et al., 2022).

Since several aspects of heatwave were already examined in the literature, we focus on several distinct questions here. First, we want to understand the extent of the heatwave, thus, our analysis covers a wider region than the relatively small rectangular regions originally proposed by Philip et al. (2022), McKinnon and Simpson (2022) and Bercoff-Hickey et al. (2022). Second, as suggested by Stone (2019), we concentrate on the political regions (Canadian provinces and the states of the United States of America) rather than on somewhat arbitrary chosen rectangular regions. This choice has the advantage that adaptation policies in Canada and the USA are often applied on the provincial/state level, and it avoids potential selection bias effects

associated with regions defined a posteriori. Second, we leverage the publication of ERA5 data back to 1940 to carry out analysis of the return period back to this earlier start date. And lastly, since this heatwave was a prolonged event, we conduct an attribution analysis not only for TXx, but also for longer periods.

The manuscript is structured as follows: in Section 2 we provide regional information about the heatwave including the its extent and discussion on its duration. The analysis of the rarity of the temperature maxima is presented in Section 3, the evaluation of temperature maxima variability in Section 4 and the attribution results are described in Section 5. The main conclusions are summarized in Section 6. The manuscript contains supplementary material.

2. Spatial extent of the 2021 heatwave

To characterize the heatwave in terms of its spatial extent, duration and strength, we used maximum air temperature at 2 m from the recently updated ERA5 reanalysis (Hersbach et al., 2020b) from 1940 to 2022. Generally, ERA5 has been proven to provide reliable maximum air temperatures over Europe (Velikou et al., 2022), but has also been used in studies focusing on the 2021 heatwave in North America, including Philip et al. (2022) and Thompson et al. (2022). Here, we consider impacted Canadian provinces and USA states using their political borders, not only because it is easier to use the regional numbers for policy making decisions, but also because the temperature patterns were relatively uniform in those regions.

The broad geographical extent of the event is illustrated in Fig. 1, where spatially resolved maximum daily temperature anomalies relative to the maximum observed between 1991 and 2020 in the Canadian provinces of British Columbia, Alberta, Saskatchewan as well as Washington and Oregon states in the USA are shown. These regions were chosen based on the fact that in 2021 within several days from each other they experienced local and regional temperature records and these records were associated with the same synoptic system (Bartusek et al., 2022, Fig. 1). The days shown in Fig. 1 are those on which 2021 temperature maxima occurred in these regions (see also Table 1).

In Oregon, where the maximum was observed on June 28th 2021, the temperature anomalies were positive for the whole region; however, the eastern border region and a small southwest part of the coast experienced lower anomalies than central and northern parts of the state. On June 29th, maxima were observed in Washington and British Columbia. While in Washington the anomalies were around 9 °C for the whole state, in British Columbia more spatial variability is seen. Nonetheless, the whole of British Columbia had positive anomalies on that day and for the most of the province extreme heat alerts were issued. For Alberta, which experienced the highest temperatures on June 30th, similar conclusions apply, with the difference that the central and northern parts of the province experienced higher anomalies rather than the southern border. In Saskatchewan, the largest maximum temperature anomaly was observed on July 2nd 2021. As seen in Fig. 1(d), temperature anomalies on that day were relatively uniform across the province with the exception of three small blue patches corresponding to large lakes. Based on this information, we consider it justified to analyse the heatwave based on temperatures averaged across these states and provinces.

2.1. Heatwave duration

One of the reasons why heatwaves are so deadly is the prolonged heat stress exposure (Koppe et al., 2004; Kenney et al., 2014). According to a commonly used definition (e.g. Perkins and Alexander, 2013; Perkins-Kirkpatrick and Gibson, 2017), a heatwave occurs when three or more consecutive days experience daily maximum temperatures higher than 90th percentile of daily maximum temperature for a 15 day running window surrounding this day during for a base period. Using

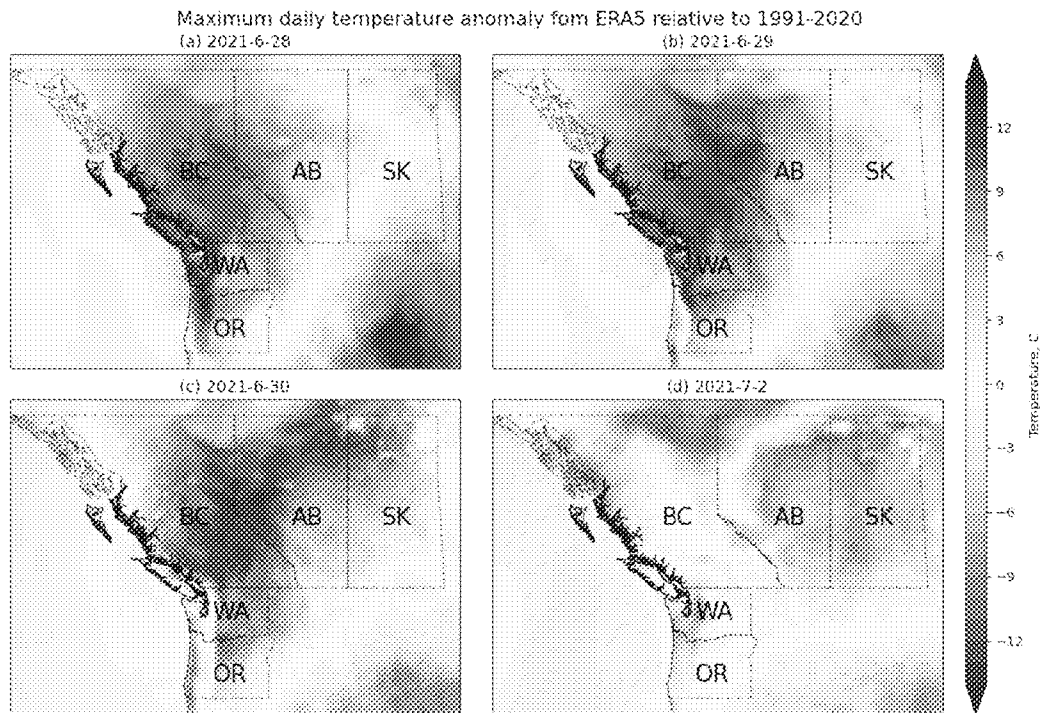


Fig. 1. ERA5 daily maximum temperature anomaly in British Columbia (BC), Alberta (AB), Saskatchewan (SK), Washington (WA) and Oregon (OR). Anomalies are calculated relative to the maximum over the years 1991–2020 over a 31 day period centred on the event.

Table 1

2021 heatwave start dates, end dates, duration and TXx, TX3x and TX7x anomalies based on ERA5 data relative to 1940–1959 for the provinces and states listed.

Region	Start	End	Duration	Peak date	TXx (anomaly)	TX3x (anomaly)	TX7x (anomaly)
BC	6/25	7/1	7 days	06/29	32.1 (9.3) °C	31.5 (9.4) °C	28.9 (8.1) °C
AB	6/25	7/2	8 days	06/30	35.4 (7.0) °C	34.7 (7.2) °C	32.0 (6.1) °C
SK	6/28	7/3	6 days	07/02	33.9 (4.6) °C	33.0 (4.6) °C	30.3 (3.8) °C
WA	6/20	7/1	12 days	06/29	40.2 (8.8) °C	39.1 (8.6) °C	36.0 (6.8) °C
OR	6/25	7/7	13 days	06/28	37.3 (5.0) °C	36.5 (5.0) °C	34.1 (3.6) °C

this definition we calculate the 2021 heatwave duration in the chosen regions with the base period of 1991 to 2020.

As shown in Table 1, the heatwave lasted at least six days in all regions considered, with Oregon and Washington experiencing more prolonged heatwaves lasting thirteen and twelve days respectively. To illustrate the heatwave duration in one of the regions, Fig. 2 shows daily maximum 2-m air temperature for 2021 over the period from June 1st to July 31st (red line, $T_{max}(2021)$) with the 90th percentile of the daily maximum temperatures for the base period (grey line, T_{max} (90th perc 1991–2020)) for British Columbia. The red shaded region shows the longest heatwave of the period. We illustrate the results for that specific region, because according to Table 1 British Columbia experienced the highest anomalies relative to 1940–1959, making the event there most extreme.

Based on this information, and since for most regions the seven day period covers the most extreme heat, we decided to analyse not only TXx or annual maximum daily maximum temperature, but also TX7x, the annual maxima of 7 day average daily maximum surface air temperature, or the warmest week of the year. We also provide analysis of TX3x (the annual maxima of 3 day average daily maximum surface air temperature), a commonly used heatwave characteristic (e.g. Kew et al., 2019; Wehner et al., 2018). Furthermore, the three-day period corresponds to the time frame when in most of the regions the temperature exceeded the 99th percentile.

3. Return period of the 2021 heatwave

3.1. Analysis based on ERA5 data from 1940 to 2022

After averaging the ERA5 daily maximum temperatures over each region, we analysed annual maxima of 1 day, 3 day and 7 day mean daily maximum temperatures (TXx, TX3x and TX7x). In each region for each time series, we fitted a non-stationary generalized extreme value distribution to the data over the period from 1940 to 2022, with the location parameter being linearly dependent on the ERA5 global mean surface air temperature (GSAT) anomalies (Morice et al., 2021) smoothed with a 4 year running mean. The value for 2021 event was included in the fit, although we are aware of the heated discussion in the scientific literature on whether it is the correct approach (Philip et al., 2020; Van Oldenborgh et al., 2021; Miralles and Davison, 2023). We also want to draw the reader's attention to the fact that the 2022 TXx, TX3x and TX7x (i.e. observations from after the event of interest) were also used in the fit. While there is a possibility that the return periods would somewhat change with 2022 data excluded, we wanted to take advantage of as long as possible timeseries to allow for more accurate return period estimates (Philip et al., 2020; Van Oldenborgh et al., 2021; Thompson et al., 2023).

Based on the timeseries and the histograms in Fig. 3, one can see that record TXx values in British Columbia and Alberta occurred in

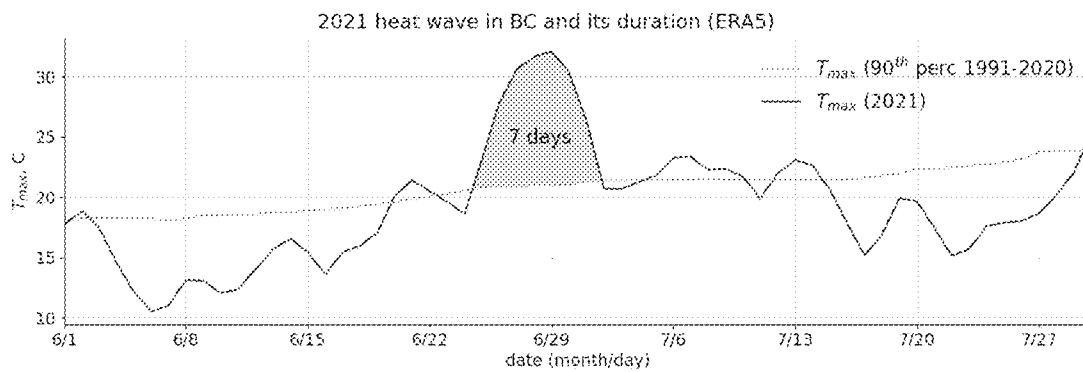


Fig. 2. ERA5 heatwave in British Columbia (BC).

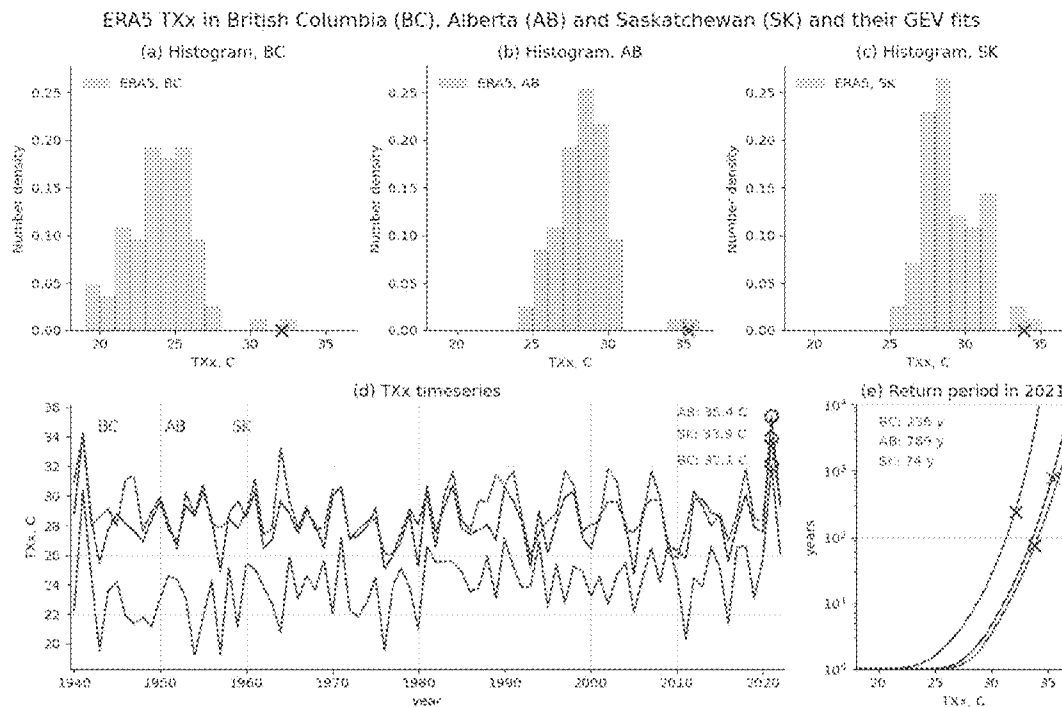


Fig. 3. ERA5 TXx histograms (panels (a)–(c)), timeseries (panel (d)) and return period curves (panel (e)) shown in blue for British Columbia (BC), in red for Alberta (AB) and in green for Saskatchewan (SK). The 2021 values are shown with crosses (panels (a)–(c), (e)) or circles (panel (d)).

2021, however, comparable values were observed in 1941. Furthermore, 1941 was a year of absolute TXx maximum in Saskatchewan based on the ERA5 data, exceeding the 2021 value by 0.1 °C, although 2021 TX3x and TX7x were record maxima in this region. As shown in Fig. 4, 1941 values were not as high in Washington and Oregon, making 2021 an exceptional year in these states. To quantify the rarity of the 2021 values, we calculated the return period of the 2021 TXx, TX3x and TX7x based on the previously described non-stationary GEV fits, using a location parameter corresponding to 2021. The results for each region including corresponding 90% confidence intervals (CIs) estimated by bootstrap resampling all TXx, TX3x and TX7x and corresponding GSAT values with replacement 1000 times are summarized in Table 2. The CIs beginning with > indicate an infinite upper bound. The TXx return period curves for the Canadian provinces and the US states shown in Figs. 3(e) and 4(d) respectively.

In British Columbia, the return period of TXx values as large as in 2021, is 236 (CI: > 52) years. While our return period estimate for British Columbia is noticeably different from those previously published for different rectangular regions (Philip et al., 2022; Thompson et al., 2022; McKinnon and Simpson, 2022; Bercos-Hickey et al., 2022), the 2021 TXx return period of 822 (CI: > 118) years in Washington

is much closer to those estimates. A similar return period of 769 (CI: > 124) years was calculated for Alberta. In Saskatchewan and Oregon the return periods are somewhat lower, namely, 75 (CI: 32–966) and 163 (CI: > 35) years respectively. It is not surprising that Saskatchewan's and Oregon's return periods are lower than those of British Columbia, Alberta and Washington, because those regions were toward the edges of the area affected by the heatwave (see Fig. 3) and their TXx anomalies (see Table 1) were approximately half as large as for British Columbia, Alberta and Washington.

Based on results shown in Table 2, return periods for TX3x were, in general, of the same order of magnitude as those for TXx. For Canadian provinces except Saskatchewan, the return periods were slightly higher than for TXx, while for Oregon and Washington state, they were slightly lower. For TX7x, the return periods in all regions except Oregon were approximately a factor of two lower than those of TXx and TX3x. In Oregon, the return period is almost 20 times lower than that of TXx and 8 times lower than TX3x, 8 (CI: 4–36) years.

The reason why the return period in Oregon for TX7x is so much lower than for the other regions is the inclusion of 2022 data into our analysis. In late July 2022, Oregon experienced a long heatwave, and although individual daily temperatures in 2022 did not reach 2021

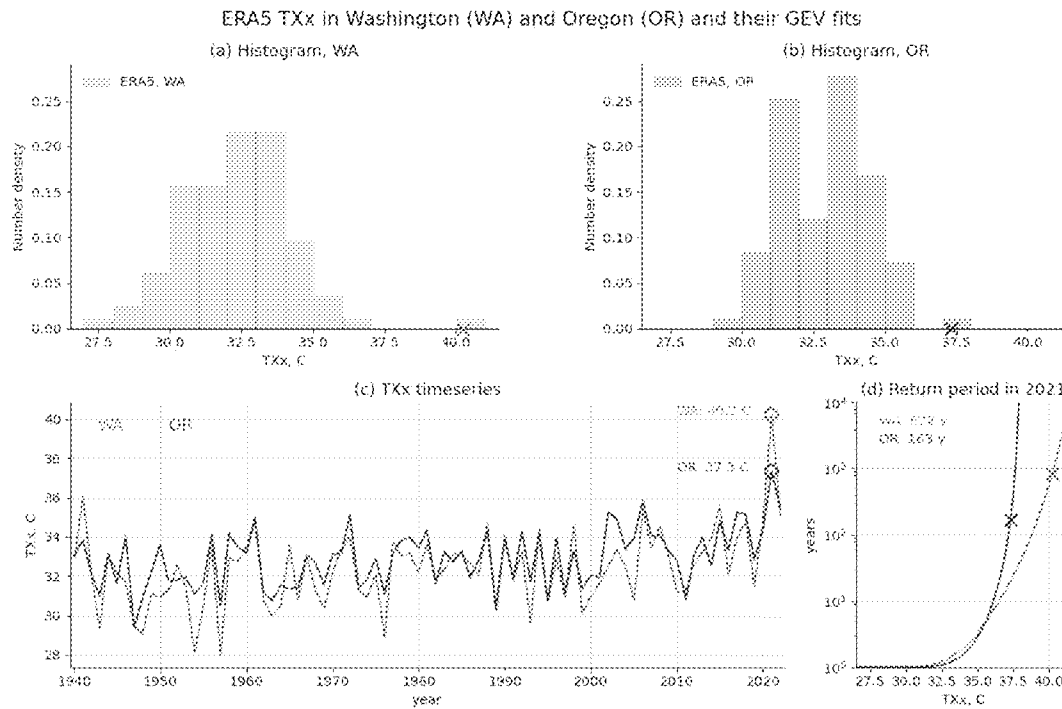


Fig. 4. ERA5 histograms (panels (a)–(b)), timeseries (panel (c)) and return period curves (panel (d)) shown in orange for Washington (WA) and in blue for Oregon (OR). The 2021 values are shown with crosses (panels (a)–(b), d)) or circles (panel (c)).

maxima, the high temperatures persisted longer, resulting in a 2022 TX7x being 0.5 °C warmer than that in 2021. At the same time, 2021 still holds the record for TXx and TX3x.

3.2. Sensitivity to the inclusion of 1940s ERA5 data

An important question, which arises looking at our estimations of return periods for the 2021 event is why the TXx return period values for BC are so much lower than for Washington and the rectangular regions used in previous studies. The main reason for the observed differences is the inclusion of the 1940–1949 period in our analysis. As shown in Fig. 3, 1941 was a year with another historic maximum in Western Canada, and although TXx was generally not as high as in 2021, taking into consideration lower GSAT in 1941, the influence on the 2021 return period estimation is noticeable. For example, the return period of the 2021 heatwave for BC TXx calculated using data from only the 1950–2021 period is 1152 (CI: > 126) years, which is more comparable with the return period for Washington based on 1940–2022 timeseries. As already noted, 1941 was not as extreme in Washington and Oregon, thus the inclusion of 1940–1949 data does not have a large effect on return periods for these states. The return period values for all regions and all variables based on 1950–2021 period can be found in Table S1 and fitted GEV parameters in Table S2. Furthermore, if considering timeseries from 1942 onward the return periods in all regions are virtually the same as if considering timeseries starting in 1950. This indicates that the 1941 event was predominantly responsible for the change in the return periods.

We also applied our analysis to the rectangular region defined by Philip *et al.* (2022), referred to hereafter as the WWA (World Weather Attribution) region. For the 1940–2022 data, the TXx return period yields 775 (CI: > 118) years, whereas for the 1950–2021 period, the same as considered by the authors of the study, it is 1217 (CI: > 136) years, consistent with their result. While the TXx return period for the WWA region is similar to that for Washington state, it is substantially higher than the return period for British Columbia. Furthermore, applying a similar analysis as in Section 3.1 to the 1941 event in British Columbia (using 1941 GSAT), we found TXx, TX3x and TX7x return

periods higher than those in 2021, of 735 (CI: > 135), 589 (CI: > 114) and 355 (CI: > 85) years respectively. Although the yearly maxima values for 1941 anomalies were slightly lower, so was the GSAT for 1941, resulting in higher return periods.

One could raise a legitimate concern in the quality of 1940–1949 data from ERA5, arguing that the dataset is fairly recent and for the preliminary version for the 1950s some issues were reported (Bell *et al.*, 2023). To validate the existence of the 1941 heat wave, we considered three sources of information. First, we analysed data from the Western Canadian weather stations available from the Adjusted and Homogenized Canadian Climate Data (AHCCD) (Vincent *et al.*, 2020). In total, the data from 111 stations covering both 1941 and 2021 heatwaves is available in British Columbia, Alberta and Saskatchewan. Example TXx timeseries for three stations in each of these provinces are presented in Fig. 5 with grey lines. It is obvious from Fig. 5 that for these nine stations, 1941 was an extreme year, with TXx comparable in magnitude with 2021 value. Similar results were obtained for the majority of other stations not shown here.

Second, we examined the year of the absolute maximum of TXx in the HadEX3 dataset (Dunn *et al.*, 2020). Since HadEX3 contains gridded TXx values from 1901 to 2018, we could not calculate regional averages the same way as we did for ERA5, however determining the year of the absolute TXx maximum can provide a quality check. HadEX3 data shows that for most of British Columbia, as well as for northern Saskatchewan and Alberta, 1941 was the year of the highest observed TXx (Fig. S2).

Lastly, we considered the records from the local newspapers. In the issues of the Victoria Daily Times from 15th to 30th of July, one can find reports of an “unprecedented heat wave”, “heat-related deaths” and the fact that the temperatures beat previous records from 1924 (The Victoria Daily Times, 1941a,b). While those statements cover mostly Vancouver and Vancouver Island, they still give an insight that 1941 was an extraordinary year. One can also find reports of the record temperatures in Alberta and Saskatchewan in the middle of July 1941 (The Victoria Daily Times, 1941c). Thus all three data sources support the ERA5 result that 1941 saw an exceptional heatwave in Western Canada.

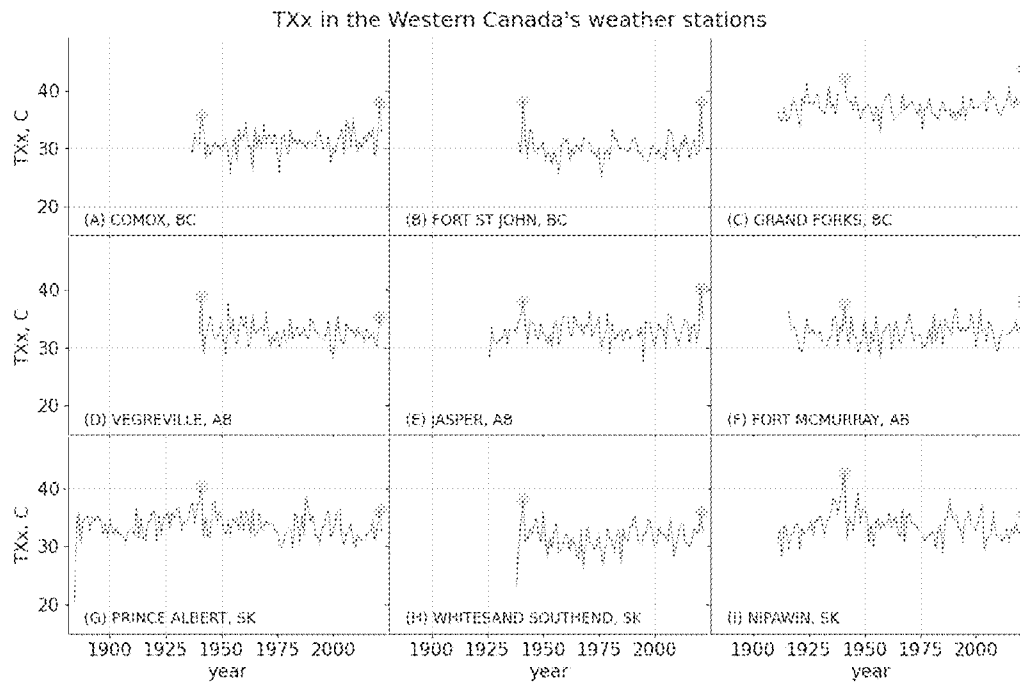


Fig. 5. TXx in Western Canadian weather stations based on the AHCCD record. Yellow circles show 2021 values and blue circles represent 1941 values.

Our findings emphasize the uncertainties associated with the calculation of return periods of several hundreds years based on 70–80 years of data. In particular, using only the data after 1950 we would infer that the 2021 event was a 1 in 1200-yr event in British Columbia, whereas an apparently even rarer event occurred in 1941, only 80 years ago. Or over Saskatchewan, we would infer that the 2021 event was a 1 in 100 year event using data since 1950, while a heatwave which was even hotter in absolute terms occurred in 1941. One cannot calculate with a high degree of certainty return periods exceeding several times the length of available observations in the area. Our results highlight the importance of considering as long as possible timeseries for the GEV fit and return period estimates. Inclusion even of one additional point can change the results drastically and it is in particular important for the events that exceed generational memory. As Philip et al. (2022) state, more studies are needed to understand the GEV analysis on annual maxima with short records and very extreme values, while Zeder et al. (2023) highlight the importance of communication of the uncertainty intervals on the return period estimates from the short observational records.

4. Evaluation of variability in maximum temperatures in CMIP6 data

Before using the CMIP6 data for attribution it is necessary to evaluate the quality of internal variability in maximum temperatures relative to the reanalysis. We used daily maximum air temperature data from 161 simulations from 22 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). We used data from the CMIP6 historical experiment (1940–2014) combined with SSP2-4.5 scenario (2015–2022) (O'Neill et al., 2016). All available simulations, except those with existing formatting issues, mismatched calendars, and those with reported *tasmax* variable errors were used in the analysis. For each time period, CMIP6 data were regridded onto an $0.5^\circ \times 0.5^\circ$ grid. Then, area averaged daily maximum air temperature (T_{max}) was calculated for each region. For TXx, the annual maxima of T_{max} were calculated, while for TX3x and TX7x the annual maxima

of the running T_{max} means over three and seven days respectively were calculated. For each variable and individual simulation, anomalies relative to 1940–1959 were obtained. We use 1940–1959 as a reference because it is the earliest available 20-yr period in ERA5 data and thus is closest to the preindustrial climate.

We analysed the standard deviations of TXx anomalies in ERA5 and in individual CMIP6 simulations for 1940–2022. In Fig. 6 we show only the values for TXx in British Columbia (panel (a)) and Saskatchewan (panel (b)) as the most extreme cases. The results for the other regions can be found in Fig. S3. It is clearly apparent that the standard deviation of TXx in British Columbia is much higher in ERA5 than almost all CMIP6 simulations (Fig. 6(a)). By contrast, in Saskatchewan the ERA5 standard deviation is smaller than the standard deviations in most CMIP6 models (Fig. 6(b)). That indicates that model variability in British Columbia is much smaller than the variability in the reanalysis data, while in Saskatchewan the model variability for most simulations is larger than the ERA5 variability. The same is true for TX3x and TX7x. Moreover, British Columbia is the only region we considered where ERA5 variability is larger than the simulated one. For all other regions, CMIP6 variability is larger than that of ERA5, but the magnitude of the differences varies from region to region, with Oregon and Saskatchewan having the largest differences (see Fig. S3).

Consistent with these results, Fig. 7 shows the geographical pattern of the ratio of standard deviation of TXx in CMIP6 to ERA5, indicating that the models tend to underestimate the variability relative to ERA5 over the oceans and many coastal regions, while they tend to overestimate the variability in the continental interior of North America. At the same time, for British Columbia, in addition to the coast, for the most of the interior part of the province (with exception of Kootenay region) the variability is underestimated. Since there is no obvious indicator (e.g., topography), why the TXx variability in British Columbia is lower, that question is deferred to the future studies. However, Fig. 6 indicates that this result is systematic across the CMIP6 models, and is not driven by one or two outliers.

To better compare the variability in TXx in ERA5 reanalysis and CMIP6 simulations, Fig. 8 compares TXx data from 1940 to 2022 from

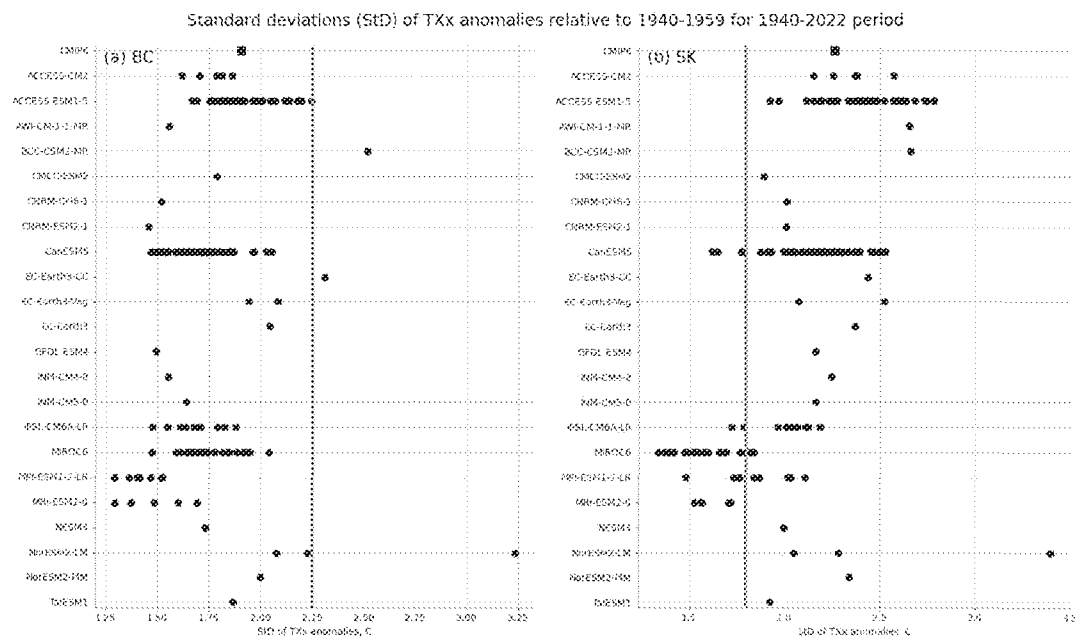


Fig. 6. Standard deviation (Std) of TXx anomalies in British Columbia (a) and Saskatchewan (b) in the 1940–2022 period. The circles represent the values for individual model realizations, the square shows a CMIP6 multi-model value weighted by the number of realizations in the model ensemble. The red vertical line depicts the ERA5 value.

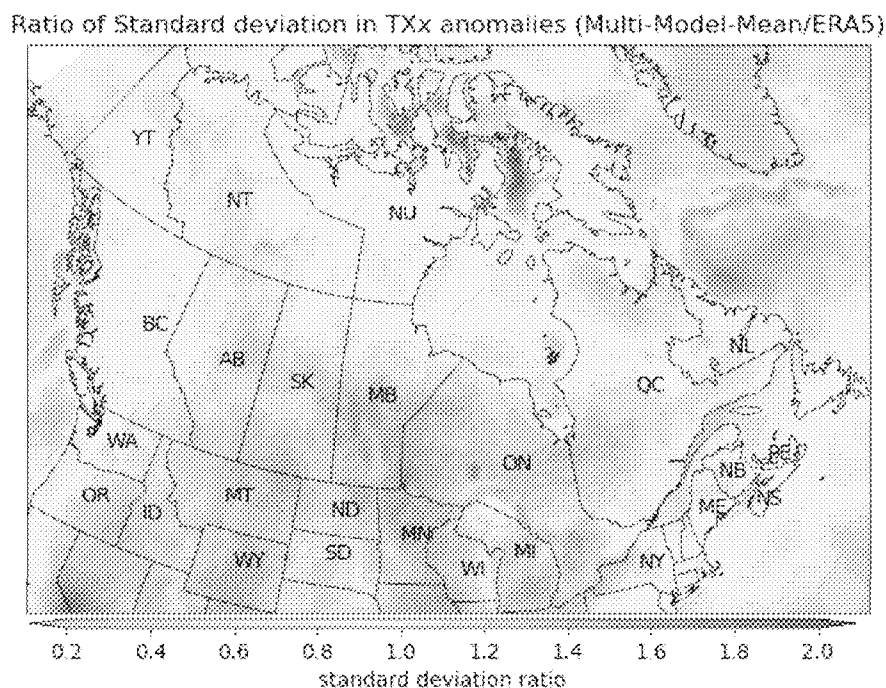


Fig. 7. Ratio of the TXx standard deviation in CMIP6 models to that in ERA5 for the period from 1940 to 2022.

ERA5 (red line) with the weighted CMIP6 multi-model mean (blue line) and the minimum and maximum across the CMIP6 ensemble (blue shading). One can see, that overall, in British Columbia (panel (a)), the ERA5 TXx anomalies span the range of CMIP6 anomalies and anomalies as large as those in 1941 and 2021 were only simulated just a few times. By contrast, in Saskatchewan (panel (b)), the CMIP6 the maximum and minimum borders are much higher/lower than the ERA5 data.

Figs. 6 and 8 indicate that for the period of interest, for British Columbia, CMIP6 models tend to underestimate TXx variability, making the probability of the 2021 event too low; for Saskatchewan the situation is the opposite, and simulated variability that is higher than observed values dominate the distribution making the simulated probability of the 2021 event too high. The differences in variability help explaining the differences in the reanalysis and CMIP6 return periods

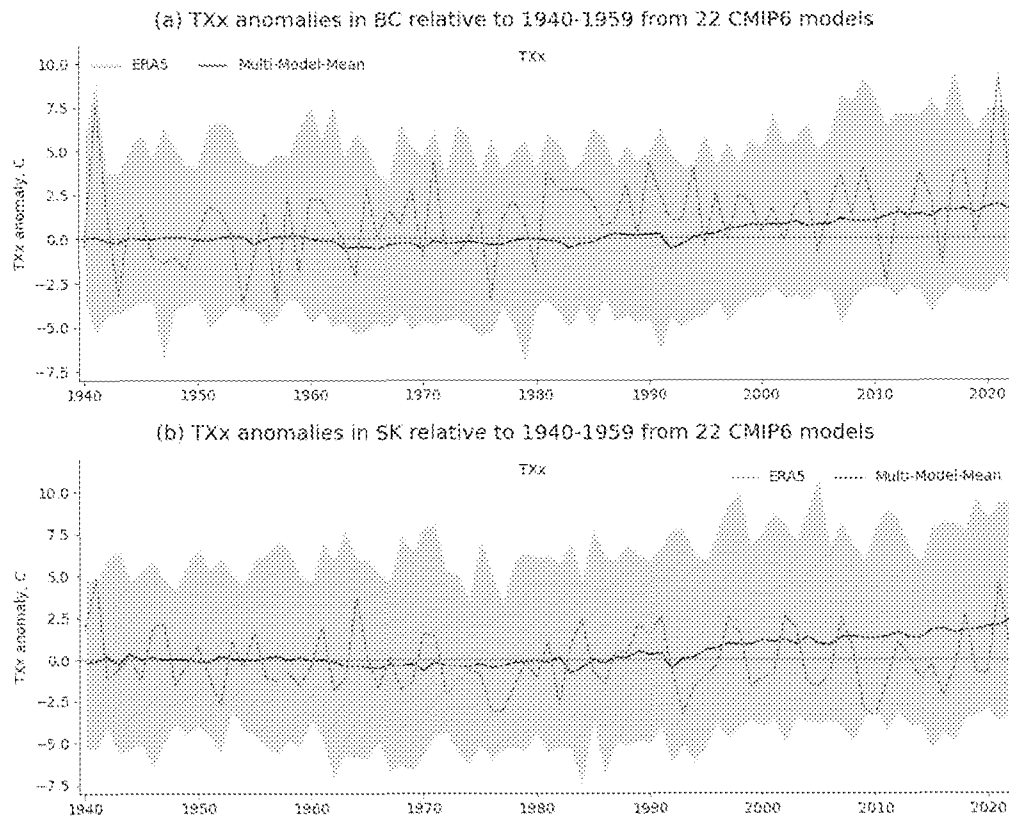


Fig. 8. TXx anomalies in BC (panel (a)) and SK (panel (b)) from 1940 to 2022 relative to 1940–1959 period. Red lines show the timeseries from ERA5, while the blue lines show the CMIP6 multi-model mean and the blue shows minimum and maximum in the multi-model ensemble.

outlined in Section 5. In particular, the modelled return periods in British Columbia are noticeably higher than those estimated from reanalysis, while in other provinces they are lower, with Saskatchewan being the most extreme case.

5. Attribution of the 2021 event

5.1. Data and method

To attribute an extreme event to climate change, the probabilities of an event in the factual (i.e. the current climate) and counterfactual (natural forcing only or pre-industrial climate) world (e.g. Allen and Stott, 2003; Seneviratne et al., 2021) are compared. For the factual world, we used a 20 year period centred at 2021 (2011–2030) from the concatenated historical and SSP2-4.5 scenario (O’Neill et al., 2016). Since, most of the simulations from the Detection and Attribution Model Intercomparison Project (DAMIP) (Gillett et al., 2016) end in 2020, we used data from the historical experiment over the quasi-preindustrial period of 1850–1900 as a counterfactual. To provide projections of the probability of a comparable event at the end of the 21st century, we used data for 2081–2100 from the SSP2-4.5 scenario. SSP2-4.5 is considered to be an “intermediate” scenario and is associated with 2.7 °C global near-surface air temperature (GSAT) warming in 2081–2100 relative to 1850–1900 (IPCC, 2021).

We fit stationary GEV distributions to the CMIP6 multi-model ensemble for each period and then calculate the return periods for an event of the same magnitude as the 2021 event in ERA5 anomalies (Table 2). A similar approach was used in attribution analysis of the maxima of two-day precipitation in British Columbia (Gillett et al., 2022). We choose to fit stationary distributions here because we focus on shorter time periods (51 and 20 years for the preindustrial and current and future climate respectively), where the climate change signal is relatively stable, unlike the 83 year period analysed in ERA5 data.

5.2. Event attribution of TXx in Alberta

The results of the TXx attribution analysis for Alberta are presented in Fig. 9. In this section we concentrate on Alberta rather than on British Columbia for two reasons: first, the return period of 2021 TXx was higher in Alberta, meaning that the 2021 heat wave was rarer in Alberta. Second, as shown in Section 4, the CMIP6 variability is closer to the observed in Alberta resulting in more robust estimates of the return periods.

In Fig. 9(a), histograms of TXx anomalies for the current climate (2011–2030) are shown in orange, for the quasi-preindustrial (1850–1900) in green, and for the future climate (2081–2100) in blue. The fitted GEV distributions are shown with solid lines in corresponding colours, with shaded areas depicting the 90% CIs obtained from bootstrap re-sampling. The goodness of the fit is illustrated by the Q–Q, or quantile–quantile, plot (Fig. 9(b)). Overall, the GEV distributions fit the simulated values very well.

In panel (a), one can see that in comparison to the green histogram, the orange histogram and GEV fit are shifted towards higher anomalies values indicating higher TXx in 2011–2030. The blue histogram is shifted even further to the right, meaning there is an even higher probability of larger TXx values by the end of the century under the SSP2-4.5 scenario. Based on the standard deviations of the fitted GEV functions, the 2011–2030 distribution is slightly wider than the 1850–1900 one and the 2081–2100 is wider still. The latter is visually noticeable in the figure as well. Several factors contribute to the widening of the distributions. First, differences in the equilibrium climate sensitivity of the CMIP6 models, and second a possible increase of the variability of the extremes in the warming climate (Seneviratne et al., 2021). Differences in warming rates between models represent real uncertainty in how the climate will respond under the SSP2-4.5 scenario, and hence this broadening of the distribution in panel (a) represents real uncertainty in how TXx is projected to change under this scenario. By

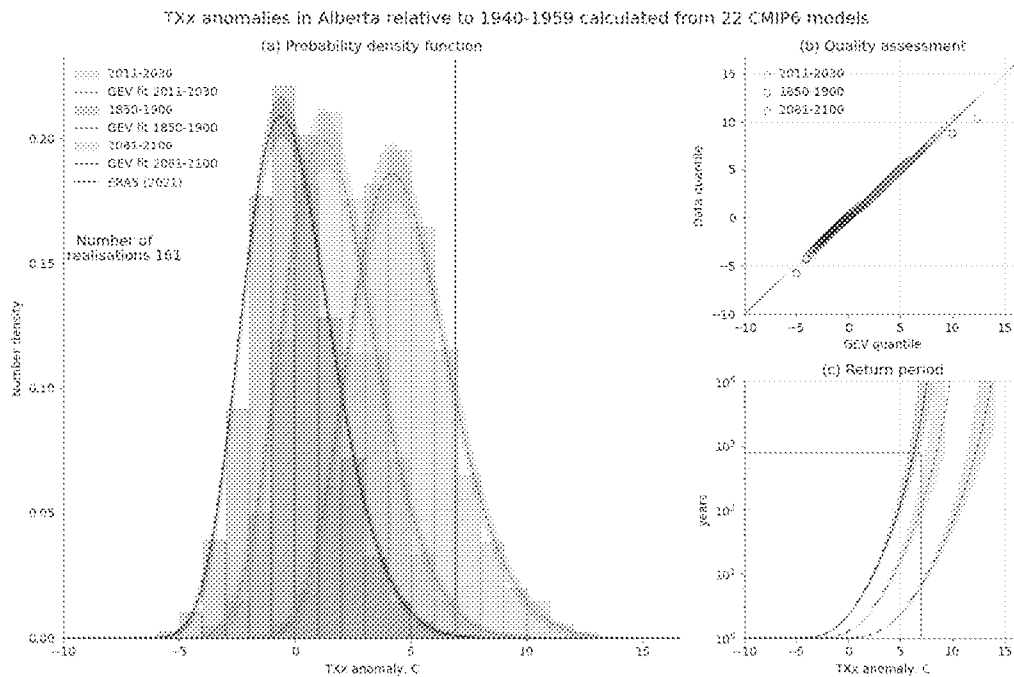


Fig. 9. TXx CMIP6 probability density function (panel (a)), QQ-plot (panel (b)) and return periods (panel (c)) for Alberta. The values corresponding to the quasi-preindustrial climate (1850–1900) are shown in green, for the current climate (2011–2030) in orange and for the 2081–2100 period under SSP2-4.5 scenario in blue. The shaded intervals in panels (a) and (c) show the 90% CIs obtained from bootstrap re-sampling. In panels (a) and (c), 2021 ERA5 TXx anomalies relative to 1940–1959 are shown with vertical red lines, and the ERA5 TXx return period is shown with the horizontal red line in panel (c).

carrying out our analysis in this way, rather than making it conditional on a particular change in global mean temperature, our return period and risk ratio estimates will reflect this uncertainty in the climate response.

Based on the GEV fits, we also assessed return periods of the 2021 event from CMIP6 models. Results are presented in Fig. 9(c) and Table 2. In Fig. 9(c), as for the other panels, the green colour corresponds to the quasi-preindustrial climate, the orange to the current climate and the blue one to the projections under the SSP2-4.5 scenario at the end of the 21st century. The solid lines show the return periods based on GEV fits and shaded regions show 90% CIs from the bootstrap re-sampling. The red lines show the TXx anomaly and the ERA5 assessed return period for the 2021 event.

Fig. 9(c) and Table 2 show that in the quasi-preindustrial climate TXx anomalies as high as observed in 2021 were extremely rare with an estimated return period of 2322 (CI: 889–22043) years, while the return period in the current climate based on CMIP6 data is 98 (CI: 62–286) years. We hence calculate a risk ratio of 24 (CI: 5.6–217) for an event at least as strong as that observed in 2021 in Alberta (Table 3). The CMIP6 best estimate of the return period for the current climate is almost eight times smaller than that estimated from ERA5, although the CIs overlap. Under the SSP2-4.5 scenario, by the end of the 21st century, events comparable to the 2021 TXx in Alberta will become much more frequent, with an estimated return period of 1 in 6.2 (CI: 5.5–7.3) years, making it 16 (CI: > 9.9–45) times more likely relative to the current climate (see Table 3).

We also calculate the intensity of an event of the same return period as the 2021 TXx (a 1 in 769 years event based on ERA5) in CMIP6 ensemble. In the current climate, according to CMIP6 data, TXx anomalies of 8.5 (CI: 7.4–9.3) °C would have the same return period as the 2021 event in ERA5 data, whereas in the quasi-preindustrial climate anomalies of 6.3 (CI: 5.7–6.8) °C would be as rare. By the end of the century under the SSP2-4.5 scenario, the intensity of a comparable in rarity event would increase to 12.3 (CI: 11.4–13.2) °C in terms of anomalies. While the intensity of the 1 in 769 year TXx in the current climate in CMIP6 models is somewhat higher than the

observed 2021 value in ERA5, we have shown earlier that the best estimate of the return period from CMIP6 is lower than that from ERA5, resulting in an overestimation of the 1 in 769 years event intensity from CMIP6 data for the current climate. This could relate in part to uncertainty in the estimation of such long return periods from the short periods of observations (see Section 3.2) as well as higher than observed variability in CMIP6 data. While we are of the recent progress on correction for both of those factors (e.g. Salpratz et al., 2019; Miralles and Davison, 2023), we defer the implementation of those corrections to the future studies. Nevertheless, our results show that human induced climate change contributed substantially to the severity of the 2021 heat wave in Alberta.

5.2.1. Event attribution for other regions and for longer duration

We repeated the calculations of return periods and risk ratios for the other regions (British Columbia, Saskatchewan, Washington, Oregon) as well as for TX3x and TX7x. TXx return periods from ERA5 and CMIP6 for the 2021 event in the current climate generally exhibit overlapping CIs, except in Saskatchewan and Oregon (Table 2), where the CMIP6 return periods are significantly lower, which is explained by the overestimated variability in CMIP6 models in these regions (Section 4). While the CIs overlap, in British Columbia the central estimate of the return period is much higher based on CMIP6, which is due to the models underestimating the variability in this region (Table 2). For the WWA region, our calculated return period of 898 (CI: 342– 2×10^6) years for the current climate is very close to the 1000 year return period reported in Philip et al. (2022). Like them, we also find that the 2021 TXx value in this region was virtually impossible in 1850–1900 period. While our estimates for the return period for the end of the century are slightly higher, unlike Philip et al. (2022) we use a milder SSP2-4.5 scenario, which is associated with the lower GSAT warming.

Similar to ERA5, the TX3x return periods are of the same order of magnitude as TXx return periods, with the Canadian provinces having return periods for TX3x which are slightly higher than for TXx and the American states having return periods for TX3x which are slightly

Table 2

Return periods (RP) for TXx, TX3x and TX7x anomalies equal to those observed in 2021. CIs are shown in brackets. CIs beginning with > indicate an infinite upper bound.

Region	TXx return period, years (CI)			
	ERA5 (2021)	CMIP6		
	1940–2022	2011–2030	1850–1900	2081–2100
BC	236 (> 52)	7668 (> 1453)	∞ (> 3.5×10^7)	41 (31–84)
AB	769 (> 124)	98 (62–286)	2322 (889–22043)	6.2 (5.5–7.3)
SK	75 (32–966)	8.0 (6.9–9.5)	45 (37–69)	1.8 (1.7–1.9)
WA	822 (> 118)	208 (112–1095)	∞ (> 10^6)	12 (11–17)
OR	163 (> 35)	14 (12–21)	352 (224– 2×10^5)	2.7 (2.4–2.9)
WWA	775 (> 119)	898 (342– 2×10^6)	∞ (> 6×10^6)	33 (26–58)
Region	TX3x return period, years (CI)			
	ERA5 (2021)	CMIP6		
	1940–2022	2011–2030	1850–1900	2081–2100
BC	212 (> 50)	9814 (> 1598)	∞ (> 10^9)	41 (32–88)
AB	891 (> 128)	138 (82–554)	4056 (1442– 10^6)	7.0 (5.9–8.0)
SK	137 (> 45)	8.2 (7.1–9.8)	52 (41–78)	1.7 (1.6–1.8)
WA	527 (> 91)	157 (90–703)	∞ (2×10^5)	10 (9–13)
OR	63 (> 19)	13 (11–19)	331 (230–13352)	2.6 (2.3–2.7)
WWA	570 (> 96)	589 (252– 10^5)	∞ (> 10^6)	23 (19–40)
Region	TX7x return period, years (CI)			
	ERA5 (2021)	CMIP6		
	1940–2022	2011–2030	1850–1900	2081–2100
BC	155 (> 42)	948 (> 377)	4×10^9 (> 48666)	13 (11–18)
AB	500 (> 84)	46 (33–91)	1119 (533–4764)	3.4 (3.1–3.8)
SK	50 (21–893)	4.9 (4.4–5.6)	26 (22–34)	1.4 (1.3–1.4)
WA	153 (> 33)	35 (26–58)	3357 (1205– 5×10^6)	3.7 (3.3–4.1)
OR	8 (4–36)	4.8 (4.3–5.4)	96 (36–152)	1.5 (1.4–1.5)
WWA	289 (> 53)	112 (70–461)	10^5 (> 5900)	7.2 (6.2–8.4)

Table 3

Risk ratios (RR) for TXx, TX3x and TX7x anomalies at least as large as those observed in 2021, calculated from CMIP6 data.

Region	TXx risk ratios		
	2011–2030/ 1850–1900	2081–2100/ 1850–1900	2081–2100/ 2011–2030
BC	∞ (> 0.77)	∞ (> 7×10^5)	189 (> 29)
AB	24 (5.6–217)	374 (142–3492)	16 (9.9–45)
SK	5.7 (4.4–8.9)	26 (21–38)	4.5 (3.9–5.4)
WA	∞ (> 3625)	∞ (> 10^6)	17 (8.2–81)
OR	24 (16–1135)	130 (93–6430)	5.3 (4.6–7.6)
WWA	∞ (> 1601)	∞ (> 10^6)	27 (8.5–45911)
Region	TX3x risk ratios		
	2011–2030/ 1850–1900	2081–2100/ 1850–1900	2081–2100/ 2011–2030
BC	∞ (> 2.4)	∞ (> 2×10^6)	226 (> 31)
AB	30 (5.4–658)	597 (210–14051)	20 (12–81)
SK	6.4 (4.7–9.7)	30 (24–45)	4.7 (4.1–5.7)
WA	39 (> 1027)	∞ (> 20129)	15 (8.2–64)
OR	24 (16–946)	128 (92–5310)	5.3 (4.6–7.5)
WWA	∞ (> 710)	∞ (> 5×10^5)	25 (8.8–4289)
Region	TX7x risk ratios		
	2011–2030/ 1850–1900	2081–2100/ 1850–1900	2081–2100/ 2011–2030
BC	3×10^6 (>0.84)	3×10^7 (>3459)	71 (27– 4×10^{11})
AB	25 (8.8–103)	325 (154–1391)	13 (9.5–26)
SK	5.4 (4.3–7.1)	19 (16–25)	3.6 (3.2–4.1)
WA	96 (30– 10^5)	914 (330– 5×10^6)	9.5 (7.2–16)
OR	20 (7.4–31)	65 (25–105)	3.2 (2.9–3.7)
WWA	119 (> 30)	1856 (> 806)	16 (9.7–63)

lower. As for ERA5, the 2021 event was substantially less rare based on CMIP6 simulations of TX7x in all cases. Based on this analysis, for all regions except British Columbia the probability of an event like that in 2021 has increased at least four times in comparison to the preindustrial climate and will increase substantially more by the end of the century under the SSP2-4.5 scenario. For British Columbia, the lower end of the risk ratio CI was hard to constrain, due to the underestimation of variability in the CMIP6 models, and the finding of an infinite return period for the present day in many bootstrap samples.

Based on CMIP6 data for British Columbia and Washington the 2021 event was virtually impossible in the pre-industrial climate. For Oregon, 2021 TXx and TX3x values were also quite rare (1 in 350 years) on the pre-industrial climate, while the TX7x value was much more frequent (1 in 96 years event). At the same time for Saskatchewan, the best estimates of the return period for the pre-industrial climate are

even lower than the best estimates from ERA5 for the current climate. We attribute these discrepancies to the variability and urge excising caution when using CMIP6 data in particularly for British Columbia and Saskatchewan. We plan to address the issue of the unrealistic variability in the future studies.

6. Conclusions

While previous work on the 2021 Pacific Northwest heatwave has generally focused on a relatively small rectangular regions, in this paper we demonstrate that record temperatures associated with this heatwave were observed much more widely across the Pacific Northwest and Prairies. In particular, we demonstrated that the heat wave affected not only the southern part of British Columbia, but extended across almost the whole province, with June 29th temperatures extreme on the provincial scale, and a British Columbia-average TXx anomaly of 9.3 °C relative to a 1940–1959 reference period. Our analysis also demonstrated that regional temperature anomalies were extremely high in Alberta and Washington state. Saskatchewan and Oregon experienced temperature extremes during the 2021 heatwave as well, although anomalies were not as high as for the other regions. Using ERA5 data, the duration of the heatwave in each region was calculated, showing that in Saskatchewan, British Columbia, and Alberta the heatwave lasted six to eight days, while the heatwave in Washington and Oregon it was longer, twelve and thirteen days respectively.

Based on a non-stationary GEV distribution fit to the ERA5 time-series for the period from 1940 to 2022, TXx observed in British Columbia in 2021 was a 1 in 236 (CI: > 52) year event, making the probability of the event considerably higher than previously thought. The reason why our estimates differ from the previously reported return periods for similar regions is the inclusion of recently released ERA5 reanalysis data for the 1940s. That data covers a heatwave which occurred in 1941, which was not as hot in absolute terms, but which was a rarer event relative to the cooler climate of the time. The return periods for 2021 TXx in Washington and Alberta exceed 700 years, while in Saskatchewan and Oregon lower return periods were observed (75 and 163 years respectively). The results for TX3x showed return periods of the same order of magnitude, while for TX7x the return periods were about two to four times smaller.

Comparing the TXx, TX3x and TX7x variability between models and observations, we found that CMIP6 models tend to underestimate the

variability in British Columbia and overestimate it in other regions, in particular in Saskatchewan and Oregon. This results in overestimation of the 2021 return periods from CMIP6 data for British Columbia and unrealistic underestimation for Saskatchewan and Oregon. Based on the CMIP6 simulations we found that the probability of the 2021 event has already increased dramatically for TXx, TX3x and TX7x and is projected to increase much more by the end of the century under SSP2-4.5 scenario. Although differences between simulated and observed variability make it hard to robustly estimate risk ratios for some of the regions, we hope to address this issue in future work.

Overall, our results highlight how sensitive return period estimates are to the region and climatological timeseries choice. We show that inclusion of just an additional decade and in particular the hot extreme of 1941 in our analysis can drastically change the results, and thus it is important to consider as long timeseries as possible. Furthermore, our analysis shows that the choice of region can influence the return periods and attribution results. When considering British Columbia as a single region, a reasonable choice based on the distribution of 2021 temperature anomalies, one finds a much lower return period for the 2021 event than if considering the rectangular (Phillip et al., 2022) region containing part of British Columbia as well as parts of Washington and Oregon states, which was also justified. Thus, particularly in the context of climate change adaptation, one cannot safely extrapolate return periods from one region to another even if the regions overlap.

CRedit authorship contribution statement

Elizaveta Malinina: Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Nathan P. Gillett:** Methodology, Supervision, Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

ERA5 data was downloaded from Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (Hersbach et al., 2020a) using `era5cli` software. CMIP6 data was obtained through ESGF nodes. Shape files for Canadian provinces were downloaded from Government of Canada (2016) and for the USA states from United States Census Bureau (2018). The AHCCD station data were obtained from ECCCdataportal. The CMIP6 data analysis was done by creating ESMValTool (Andela et al., 2022; Righi et al., 2023) recipes and corresponding diagnostics available at GitHub. The ClimextRemes package (Paciorek et al., 2018) was used to fit GEV distributions. The same methods are planned to apply for analysis of other heatwaves in the future. The example for the recent 2023 spring heatwave in Alberta is shown in Supplements S7.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.wace.2024.100642>.

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From: Steven Koonin <steven.koonin@gmail.com>
Sent: Friday, August 1, 2025 2:10 PM
To: Steven Koonin
Cc: John Christy; Ross McKittrick; Judith Curry; Roy Spencer; Josh Loucks; Seth Cohen; Travis Fisher; Steve Koonin
Subject: Re: NCA5 Review TX Floods

Oops, hit send too fast-

There was great interest/surprise in the record. So suggest we include these in a box in the final CWG or NCA5 report.

Steven Koonin

> On Aug 1, 2025, at 13:08, Steven Koonin <steven.koonin@gmail.com> wrote:
>
> I have shown the July 1900 observer's report and Roy's graph of the heaviest 2-day events in two separate presentations this week
> Steven Koonin
>
>> On Jul 28, 2025, at 12:29, John Christy <climateman60@gmail.com> wrote:
>>
>>
>> Ross et al.
>>
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>> p.s. Recall that two months later in Sept 1900, the worst hurricane death toll in US history occurred in Galveston. It was a bad year for Central TX.
>> <414780_190007_Kerrville.pdf>

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Friday, August 1, 2025 2:08 PM
To: John Christy
Cc: Ross McKittrick; Judith Curry; Roy Spencer; Steve Koonin; Josh Loucks; Seth Cohen; Travis Fisher
Subject: Re: NCA5 Review TX Floods

I have shown the July 1900 observer's report and Roy's graph of the heaviest 2-day events in two separate presentations this week
Steven Koonin

> On Jul 28, 2025, at 12:29, John Christy <climateman60@gmail.com> wrote:

>

>

> Ross et al.

>

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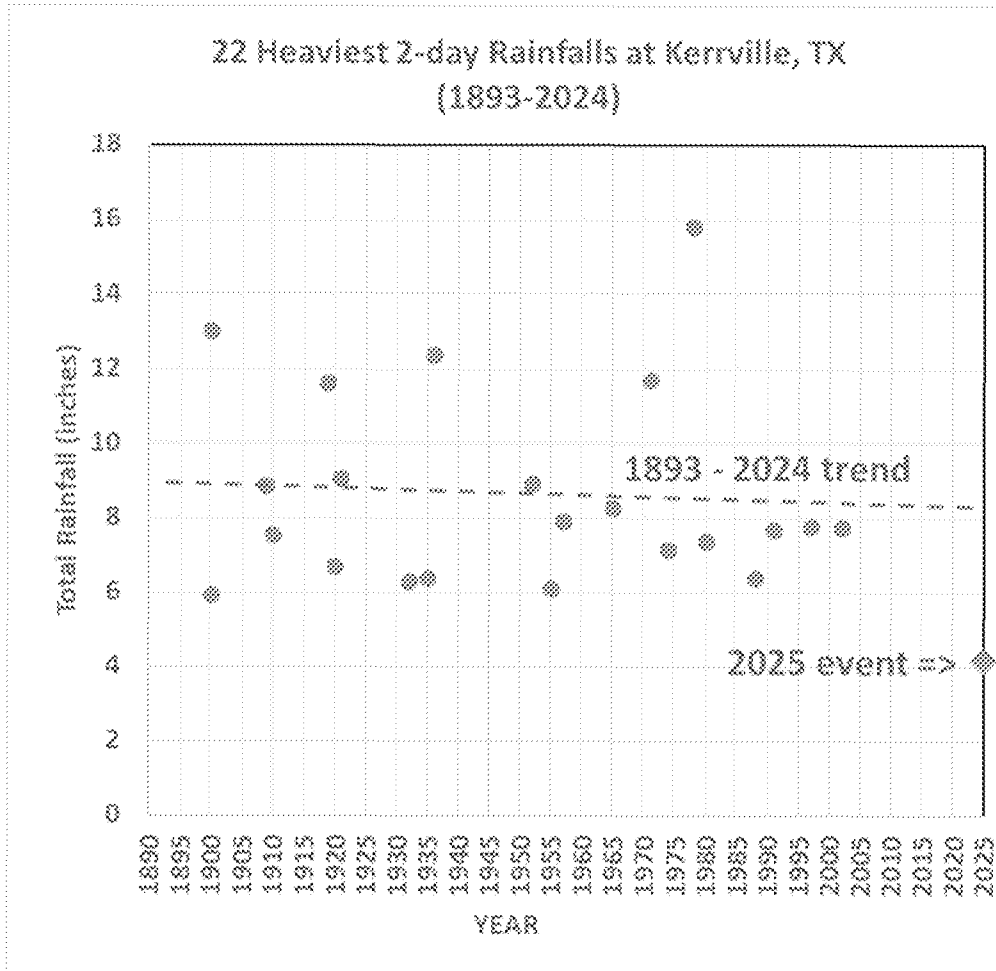
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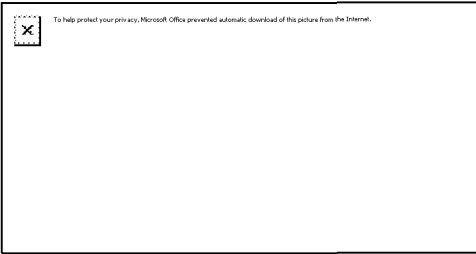
From: Roy Spencer <roywspencer@hotmail.com>
Sent: Tuesday, July 29, 2025 7:45 AM
To: John Christy; Steven Koonin
Cc: Ross McKittrick; Judith Curry; Josh Loucks; Seth Cohen; Travis Fisher
Subject: Re: NCA5 Review TX Floods
Attachments: paste.png

I plotted up the heaviest 2-day rainfalls that John provided yesterday.



The EPA has plots of trends of river flooding frequency and magnitude (1965-2015), and for most of TX they are downward:

<https://www.epa.gov/climate-indicators/climate-change-indicators-river-flooding>



Climate Change Indicators: River Flooding | US EPA

This figure shows changes in the size of flooding events in rivers and streams in the United States between 1965 and 2015. Blue upward-pointing symbols show locations where floods have become larger; brown downward-pointing symbols show locations where floods have become smaller. The larger, solid-color symbols represent stations where the change was statistically significant. Data source ...

www.epa.gov

-Roy

From: John Christy <climateman60@gmail.com>

Sent: Monday, July 28, 2025 1:50 PM

To: Steven Koonin <steven.koonin@gmail.com>

Cc: Ross McKittrick <ross.mckittrick@gmail.com>; Judith Curry <curry.judith@gmail.com>; Roy Spencer <roywspencer@hotmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>; Travis Fisher <travis.fisher@hq.doe.gov>

Subject: Re: NCA5 Review TX Floods

All

Just finished Kerrville TX data entry. Below are the heaviest 2-day events for 1893-2024. These are the 22 heaviest events (nominal 1 in 6yr occurrence - I used 6 years because it divides into 132 years evenly.). Only one of the events occurred in the 21st century - and just barely. The date represents the second of the two days. The July 4-5 2025 event produced 4.14 inches in Kerrville (which is not the source region for the floods, but representative none the less).

John C.

Kerrville TX

1	1978	8	2	15.80
2	1900	7	15	13.00
3	1936	9	16	12.37
4	1971	8	13	11.69
5	1919	8	22	11.62
6	1921	6	13	9.06
7	1952	9	11	8.90
8	1909	7	23	8.84
9	1965	6	23	8.25
10	1957	10	15	7.90
11	1997	6	23	7.76
12	2002	7	3	7.73
13	1991	12	21	7.67
14	1910	4	1	7.52
15	1980	9	8	7.35
16	1974	5	1	7.13
17	1920	8	8	6.68
18	1988	7	12	6.38
19	1935	6	15	6.37
20	1932	7	3	6.29
21	1955	7	18	6.10
22	1900	4	7	5.93

On Mon, Jul 28, 2025 at 1:17 PM John Christy <climateman60@gmail.com> wrote:

Steve

There is a bit of confusion as to which/where the 1900 gage was. We can find all of that information depending on how much we dive into this in the review of NCA5 - the 25ft was a quote from an NPR news story simply saying "near Kerrville", but later in the story they did indicate at least a 30ft rise before the gage broke. The Kerrville site USGS 08166200 shows a rise from 1.82ft to 34.29ft or 32.47ft, almost identical to the 1900 event from the observer's notes (not sure of their precision). The Kerrville site USGS 08166140 (above Bear Creek) went from 3.05ft to 34.40ft or 31.35ft. We can likely dredge up the old values from historical records, but clearly, quick rises of 30+ feet are in the historical record. The gage closest to Mystic Camp (08165500, Hunt TX used in NPR story) broke at 5:10am as it went from 7.75ft to 37.52ft.

John C.

On Mon, Jul 28, 2025 at 12:53 PM Steven Koonin <steven.koonin@gmail.com> wrote:

This is great!

But didn't the river hit 34 feet during the recent flood: <https://www.usatoday.com/story/graphics/2025/07/06/texas-cities-flooded-july-4-rain/84484814007/>

And the recent rainfall total was 10-12 inches over 3 days, whereas the 1900 total was 11.6 inches over 1 day.

Steven Koonin

On Jul 28, 2025, at 13:29, John Christy <climateman60@gmail.com> wrote:

Ross et al.

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[illegible]

id="clip47"><rect x="264" y="1251" width="612" height="592"></rect></clipPath><clipPath id="clip48"><rect x="264" y="1251" width="612" height="592"></rect></clipPath><clipPath id="clip49"><rect x="264" y="1251" width="612" height="592"></rect></clipPath><clipPath id="clip50"><rect x="264" y="1251" width="612" height="592"></rect></clipPath><clipPath id="clip51"><rect x="264" y="1251" width="612" height="592"></rect></clipPath><clipPath id="clip52"><rect x="264" y="1251" width="612" height="592"></rect></clipPath><clipPath id="clip53"><rect x="264" y="1251" width="612" height="592"></rect></clipPath><clipPath id="clip54"><rect x="264" y="1251" width="612" height="592"></rect></clipPath><clipPath id="clip55"><rect x="264" y="1251" width="612" height="592"></rect></clipPath><clipPath id="clip56"><rect x="113" y="1514" width="1231" height="96"></rect></clipPath><clipPath id="clip57"><rect x="264" y="1251" width="612" height="592"></rect></clipPath><clipPath id="clip58"><rect x="113" y="1514" width="1231" height="96"></rect></clipPath><clipPath id="clip59"><rect x="264" y="1251" width="612" height="592"></rect></clipPath><clipPath id="clip60"><rect x="113" y="1514" width="1231" height="96"></rect></clipPath><clipPath id="clip61"><rect x="264" y="1251" width="612" height="592"></rect></clipPath></defs><g clip-path="url(#clip0)" transform="translate(-264 -1252)"><rect x="264" y="1252" width="612" height="591" fill="#FFFFFF"></rect><g clip-path="url(#clip1)"><path d="M350.5 1700.5 861.5 1700.5M350.5 1655.5 861.5 1655.5M350.5 1609.5 861.5 1609.5M350.5 1564.5 861.5 1564.5M350.5 1518.5 861.5 1518.5M350.5 1473.5 861.5 1473.5M350.5 1427.5 861.5 1427.5M350.5 1382.5 861.5 1382.5M350.5 1336.5 861.5 1336.5" stroke="#D9D9D9" stroke-linejoin="round" stroke-miterlimit="10" fill="none"></path></g><g clip-path="url(#clip2)"><path d="M369.5 1336.5 369.5 1746.5M388.5 1336.5 388.5 1746.5M407.5 1336.5 407.5 1746.5M426.5 1336.5 426.5 1746.5M445.5 1336.5 445.5 1746.5M464.5 1336.5 464.5 1746.5M483.5 1336.5 483.5 1746.5M502.5 1336.5 502.5 1746.5M520.5 1336.5 520.5 1746.5M539.5 1336.5 539.5 1746.5M558.5 1336.5 558.5 1746.5M577.5 1336.5 577.5 1746.5M596.5 1336.5 596.5 1746.5M615.5 1336.5 615.5 1746.5M634.5 1336.5 634.5 1746.5M653.5 1336.5 653.5 1746.5M672.5 1336.5 672.5 1746.5M691.5 1336.5 691.5 1746.5M710.5 1336.5 710.5 1746.5M728.5 1336.5 728.5 1746.5M747.5 1336.5 747.5 1746.5M766.5 1336.5 766.5 1746.5M785.5 1336.5 785.5 1746.5M804.5 1336.5 804.5 1746.5M823.5 1336.5 823.5 1746.5M842.5 1336.5 842.5 1746.5M861.5 1336.5 861.5 1746.5" stroke="#D9D9D9" stroke-linejoin="round" stroke-miterlimit="10" fill="none"></path></g><g clip-path="url(#clip3)"><rect x="350.5" y="1336.5" width="511" height="410" stroke="#000000" stroke-linejoin="round" stroke-miterlimit="10" fill="none"></rect></g><g clip-path="url(#clip4)"><path d="M0 0 0.000104987 410" stroke="#BFBFBF" stroke-linejoin="round" stroke-miterlimit="10" fill="none" fill-rule="evenodd" transform="matrix(1 0 0 -1 350.5 1746.5)"></path></g><g clip-path="url(#clip5)"><path d="M350.5 1746.5 861.5 1746.5" stroke="#BFBFBF" stroke-linejoin="round" stroke-miterlimit="10" fill="none" fill-rule="evenodd"></path></g><g clip-path="url(#clip6)"><path d="M392 1449.5C392 1451.71 390.209 1453.5 388 1453.5 385.791 1453.5 384 1451.71 384 1449.5 384 1447.29 385.791 1445.5 388 1445.5 390.209 1445.5 392 1447.29 392 1449.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M392 1610.5C392 1612.71 390.209 1614.5 388 1614.5 385.791 1614.5 384 1612.71 384 1610.5 384 1608.29 385.791 1606.5 388 1606.5 390.209 1606.5 392 1608.29 392 1610.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M426 1544.5C426 1546.71 424.209 1548.5 422 1548.5 419.791 1548.5 418 1546.71 418 1544.5 418 1542.29 419.791 1540.5 422 1540.5 424.209 1540.5 426 1542.29 426 1544.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M430 1574.5C430 1576.71 428.209 1578.5 426 1578.5 423.791 1578.5 422 1576.71 422 1574.5 422 1572.29 423.791 1570.5

426 1570.5 428.209 1570.5 430 1572.29 430 1574.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M464 1480.5C464 1482.71 462.209 1484.5 460 1484.5 457.791 1484.5 456 1482.71 456 1480.5 456 1478.29 457.791 1476.5 460 1476.5 462.209 1476.5 464 1478.29 464 1480.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M468 1593.5C468 1595.71 466.209 1597.5 464 1597.5 461.791 1597.5 460 1595.71 460 1593.5 460 1591.29 461.791 1589.5 464 1589.5 466.209 1589.5 468 1591.29 468 1593.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M471 1539.5C471 1541.71 469.209 1543.5 467 1543.5 464.791 1543.5 463 1541.71 463 1539.5 463 1537.29 464.791 1535.5 467 1535.5 469.209 1535.5 471 1537.29 471 1539.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M513 1602.5C513 1604.71 511.209 1606.5 509 1606.5 506.791 1606.5 505 1604.71 505 1602.5 505 1600.29 506.791 1598.5 509 1598.5 511.209 1598.5 513 1600.29 513 1602.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M524 1600.5C524 1602.71 522.209 1604.5 520 1604.5 517.791 1604.5 516 1602.71 516 1600.5 516 1598.29 517.791 1596.5 520 1596.5 522.209 1596.5 524 1598.29 524 1600.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M528 1463.5C528 1465.71 526.209 1467.5 524 1467.5 521.791 1467.5 520 1465.71 520 1463.5 520 1461.29 521.791 1459.5 524 1459.5 526.209 1459.5 528 1461.29 528 1463.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M589 1542.5C589 1544.71 587.209 1546.5 585 1546.5 582.791 1546.5 581 1544.71 581 1542.5 581 1540.29 582.791 1538.5 585 1538.5 587.209 1538.5 589 1540.29 589 1542.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M600 1606.5C600 1608.71 598.209 1610.5 596 1610.5 593.791 1610.5 592 1608.71 592 1606.5 592 1604.29 593.791 1602.5 596 1602.5 598.209 1602.5 600 1604.29 600 1606.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M608 1565.5C608 1567.71 606.209 1569.5 604 1569.5 601.791 1569.5 600 1567.71 600 1565.5 600 1563.29 601.791 1561.5 604 1561.5 606.209 1561.5 608 1563.29 608 1565.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M638 1557.5C638 1559.71 636.209 1561.5 634 1561.5 631.791 1561.5 630 1559.71 630 1557.5 630 1555.29 631.791 1553.5 634 1553.5 636.209 1553.5 638 1555.29 638 1557.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M661 1479.5C661 1481.71 659.209 1483.5 657 1483.5 654.791 1483.5 653 1481.71 653 1479.5 653 1477.29 654.791 1475.5 657 1475.5 659.209 1475.5 661 1477.29 661 1479.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M672 1583.5C672 1585.71 670.209 1587.5 668 1587.5 665.791 1587.5 664 1585.71 664 1583.5 664 1581.29 665.791 1579.5 668 1579.5 670.209 1579.5 672 1581.29 672 1583.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M687 1385.5C687 1387.71 685.209 1389.5 683 1389.5 680.791 1389.5 679 1387.71 679 1385.5 679 1383.29 680.791 1381.5 683 1381.5 685.209 1381.5 687 1383.29 687 1385.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M695 1578.5C695 1580.71 693.209 1582.5 691 1582.5 688.791 1582.5 687 1580.71 687 1578.5 687 1576.29 688.791 1574.5 691 1574.5 693.209 1574.5 695 1576.29 695 1578.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M725 1600.5C725 1602.71 723.209 1604.5 721 1604.5 718.791 1604.5 717 1602.71 717 1600.5 717 1598.29 718.791 1596.5 721 1596.5 723.209 1596.5 725 1598.29 725 1600.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M736 1570.5C736 1572.71 734.209 1574.5 732 1574.5 729.791 1574.5 728 1572.71 728 1570.5 728 1568.29 729.791 1566.5 732 1566.5 734.209 1566.5 736 1568.29 736 1570.5Z"

stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M759 1568.5C759 1570.71 757.209 1572.5 755 1572.5 752.791 1572.5 751 1570.71 751 1568.5 751 1566.29 752.791 1564.5 755 1564.5 757.209 1564.5 759 1566.29 759 1568.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path><path d="M778 1569.5C778 1571.71 776.209 1573.5 774 1573.5 771.791 1573.5 770 1571.71 770 1569.5 770 1567.29 771.791 1565.5 774 1565.5 776.209 1565.5 778 1567.29 778 1569.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path></g><g clip-path="url(#clip7)"><path d="M862 1660.5 854 1652.5Z" stroke="#548235" stroke-linejoin="round" stroke-miterlimit="10" fill="#00B050"></path></g><g clip-path="url(#clip8)"><path d="M362.5 1542.5 853.5 1557.5" stroke="#4472C4" stroke-width="2.66667" stroke-linecap="round" stroke-linejoin="round" stroke-miterlimit="10" stroke-dasharray="8 10.6667" fill="none" fill-rule="evenodd"></path></g><g clip-path="url(#clip9)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="translate(323.96 1752)">0</text></g><g clip-path="url(#clip10)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="translate(323.96 1706)">2</text></g><g clip-path="url(#clip11)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="translate(323.96 1661)">4</text></g><g clip-path="url(#clip12)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="translate(323.96 1615)">6</text></g><g clip-path="url(#clip13)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="translate(323.96 1570)">8</text></g><g clip-path="url(#clip14)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="translate(314.5 1524)">10</text></g><g clip-path="url(#clip15)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="translate(314.5 1479)">12</text></g><g clip-path="url(#clip16)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="translate(314.5 1433)">14</text></g><g clip-path="url(#clip17)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="translate(314.5 1388)">16</text></g><g clip-path="url(#clip18)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="translate(314.5 1342)">18</text></g><g clip-path="url(#clip19)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="matrix(6.12323e-17 -1 1 6.12323e-17 357.344 1796)">1890</text></g><g clip-path="url(#clip20)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="matrix(6.12323e-17 -1 1 6.12323e-17 376.255 1796)">1895</text></g><g clip-path="url(#clip21)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="matrix(6.12323e-17 -1 1 6.12323e-17 395.166 1796)">1900</text></g><g clip-path="url(#clip22)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="matrix(6.12323e-17 -1 1 6.12323e-17 414.077 1796)">1905</text></g><g clip-path="url(#clip23)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="matrix(6.12323e-17 -1 1 6.12323e-17 432.988 1796)">1910</text></g><g clip-path="url(#clip24)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="matrix(6.12323e-17 -1 1 6.12323e-17 451.899 1796)">1915</text></g><g clip-path="url(#clip25)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-

DOJ 00002938

path="url(#clip45)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="matrix(6.12323e-17 -1 1 6.12323e-17 849.029 1796)">2020</text></g><g clip-path="url(#clip46)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="matrix(6.12323e-17 -1 1 6.12323e-17 867.94 1796)">2025</text></g><g clip-path="url(#clip47)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="matrix(6.12323e-17 -1 1 6.12323e-17 305.713 1624)">Total Rainfall (inches)</text></g><g clip-path="url(#clip48)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="19" transform="translate(550.152 1819)">YEAR</text></g><g clip-path="url(#clip49)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="22" transform="translate(387.85 1287)">22 Heaviest</text></g><g clip-path="url(#clip50)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="22" transform="translate(512.01 1287)">-</text></g><g clip-path="url(#clip51)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="22" transform="translate(518.87 1287)">day Rainfalls at Kerrville, TX</text></g><g clip-path="url(#clip52)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="22" transform="translate(526.423 1315)">(1893</text></g><g clip-path="url(#clip53)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="22" transform="translate(578.817 1315)">-</text></g><g clip-path="url(#clip54)"><text fill="#595959" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="22" transform="translate(585.677 1315)">2024</text></g><rect x="264.5" y="1252.5" width="612" height="591" stroke="#D9D9D9" stroke-linejoin="round" stroke-miterlimit="10" fill="none"></rect><g clip-path="url(#clip55)"><g clip-path="url(#clip56)"><text fill="#0070C0" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="24" transform="translate(640.603 1542)">1893</text></g></g><g clip-path="url(#clip57)"><g clip-path="url(#clip58)"><text fill="#0070C0" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="24" transform="translate(694.696 1542)">-</text></g></g><g clip-path="url(#clip59)"><g clip-path="url(#clip60)"><text fill="#0070C0" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="24" transform="translate(707.469 1542)">2024 trend</text></g></g><g clip-path="url(#clip61)"><text fill="#0070C0" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="24" transform="translate(704.431 1660)">2025 event</text></g></g></svg>

From: John Christy <climateman60@gmail.com>
Sent: Monday, July 28, 2025 2:50 PM
To: Steven Koonin
Cc: Ross McKittrick; Judith Curry; Roy Spencer; Steve Koonin; Josh Loucks; Seth Cohen; Travis Fisher
Subject: Re: NCA5 Review TX Floods
Attachments: Kerrville_TX_2dy.png

All

Just finished Kerrville TX data entry. Below are the heaviest 2-day events for 1893-2024. These are the 22 heaviest events (nominal 1 in 6yr occurrence - I used 6 years because it divides into 132 years evenly.). Only one of the events occurred in the 21st century - and just barely. The date represents the second of the two days. The July 4-5 2025 event produced 4.14 inches in Kerrville (which is not the source region for the floods, but representative none the less).

John C.

Kerrville TX

1	1978	8	2	15.80
2	1900	7	15	13.00
3	1936	9	16	12.37
4	1971	8	13	11.69
5	1919	8	22	11.62
6	1921	6	13	9.06
7	1952	9	11	8.90
8	1909	7	23	8.84
9	1965	6	23	8.25
10	1957	10	15	7.90
11	1997	6	23	7.76
12	2002	7	3	7.73
13	1991	12	21	7.67
14	1910	4	1	7.52
15	1980	9	8	7.35
16	1974	5	1	7.13
17	1920	8	8	6.68
18	1988	7	12	6.38
19	1935	6	15	6.37
20	1932	7	3	6.29
21	1955	7	18	6.10
22	1900	4	7	5.93

On Mon, Jul 28, 2025 at 1:17 PM John Christy <climateman60@gmail.com> wrote:

Steve

There is a bit of confusion as to which/where the 1900 gage was. We can find all of that information depending on how much we dive into this in the review of NCA5 - the 25ft was a quote from an NPR news story simply saying "near Kerrville", but later in the story they did indicate at least a 30ft rise before the gage broke. The Kerrville site USGS 08166200 shows a rise from 1.82ft to 34.29ft or 32.47ft, almost identical to the 1900 event from the observer's notes (not sure of their precision). The Kerrville site USGS 08166140 (above Bear Creek) went from 3.05ft to 34.40ft or 31.35ft. We can likely dredge up the old values from historical records, but clearly, quick rises of 30+ feet are in the historical record. The gage closest to Mystic Camp (08165500, Hunt TX used in NPR story) broke at 5:10am as it went from 7.75ft to 37.52ft.

John C.

On Mon, Jul 28, 2025 at 12:53 PM Steven Koonin <steven.koonin@gmail.com> wrote:

This is great!

But didn't the river hit 34 feet during the recent flood: <https://www.usatoday.com/story/graphics/2025/07/06/texas-cities-flooded-july-4-rain/84484814007/>

And the recent rainfall total was 10-12 inches over 3 days, whereas the 1900 total was 11.6 inches over 1 day.

Steven Koonin

On Jul 28, 2025, at 13:29, John Christy <climateman60@gmail.com> wrote:

Ross et al.

I'm putting the finishing touches on a dataset of 21 stations in Flash Flood Alley (TX) starting in 1893. Data are difficult to find and some forms have never been keyed into computer-readable files, including daily data from the Cotton Region Stations. I'm working on Kerrville today (just down river from Mystic Camp) for data prior to the regular station reports that began in 1902. I ran across this for July 1900 (attached) in which a rain total of 11.60" fell on the 15th and the observer remarked about it.

Note he says the river rose 33 ft. Recall the river rose 25ft at Kerrville in the recent July 4th flood. There is already ample evidence that bad floods happen here, but this is an example of data not keyed-in our NOAA official files that can provide better evidence to determine the likelihood of extreme events.

In any case, we can use the results of our (i.e. Ross's) analyses of these 21 stations in our review of NCA5 to give an example of what an NCA should be doing to understand and prepare for natural variability vs. climate change (and how pathetic the information was in NCA5.)

John C.

p.s. Recall that two months later in Sept 1900, the worst hurricane death toll in US history occurred in Galveston. It was a bad year for Central TX.
<414780_190007_Kerrville.pdf>

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From: John Christy [climateman60@gmail.com]
Sent: 7/28/2025 5:29:27 PM
To: Ross McKittrick [ross.mckittrick@gmail.com]; Judith Curry [curry.judith@gmail.com]; Roy Spencer [roywspencer@hotmail.com]; Steve Koonin [steven.koonin@gmail.com]; Josh Loucks [loucksj14@gmail.com]; Cohen, Seth [seth.cohen@hq.doe.gov]; Travis Fisher [travis.fisher@hq.doe.gov]
Subject: NCA5 Review TX Floods
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p.s. Recall that two months later in Sept 1900, the worst hurricane death toll in US history occurred in Galveston. It was a bad year for Central TX.

Monthly Meteorological Record of Cotton-Region Station at Kerrville, Texas during JULY, 1890.

Date.	TEMPERATURE.*			PRECIPITATION IN INCHES AND HUNDREDTHS.			State of weather.	Time observation was taken. A. M.	Time report was filed at telegraph office.	GENERAL SUMMARY.
	Max.	Min.	Mean.	Began.	Ended.	Amount.				
1	89	71	18			.00	Clear	6 ¹⁰	7 ⁰⁰	Mean temperature (obtained by dividing the sum of the mean maximum and mean minimum by two), <u>80.82</u> .
2	90	72	18			.00	"	"	7 ⁰⁰	
3	90	70	20			.00	"	"	6 ⁴⁵	
4	90	70	20			.00	"	"	6 ²⁵	Highest temperature during month and date, <u>98</u> . <u>28th & 29th</u>
5	87	70	17	5 ⁴⁵ PM	6 ⁴⁵ PM	.10	Partly Cloudy	"	6 ⁴⁷	
6	84	68	16	4 ⁴⁵ PM	7 ⁴⁵ PM	.26	"	"	6 ³⁹	Lowest temperature during month and date, <u>63</u> . <u>11th & 12th</u>
7	88	69	19			.00	Clear	"	6 ⁴²	
8	89	78	11			.00	"	"	6 ⁴²	Total precipitation during month <u>15.59</u> inches.
9	90	69	21			.00	"	"	6 ⁴⁷	
10	88	65	23			.00	"	"	6 ³⁸	Number of days on which .01 or more precipitation occurred <u>8</u>
11	89	63	26			.00	"	"	6 ³⁷	
12	92	63	29			.00	"	"	6 ³⁵	Greatest precipitation in any 24 consecutive hours <u>11.60</u> , and date <u>15th</u>
13	93	67	26			.00	"	"	6 ⁵⁰	
14	89	71	18	7 ⁴⁵ AM	8 ⁴⁵ PM	1.40	Cloudy	"	6 ³⁵	REMARKS. (Note severe storms and unusual phenomena.)
15	83	73	16	6 ⁴⁵ AM	12 ⁴⁵ AM	11.60	"	"	6 ⁵⁰	
16	89	73	14			.00	Clear	"	6 ⁵⁰	Severe rain storm occurred on 15 th causing 33 ft. rise in river at this station - Highest river has been since 1866 - Much damage to Bridges, land, fences, crops, cotton gins and power-plants in path of flood. Flood came suddenly during night - Began rising 9 P.M. - highest 1 ⁴⁵ AM. - Receding 3 AM Roads very badly damaged - all telegraph & telephone service delayed several days - No mail for 6 days - No trains 11 days - Damage to Bridges and track on S.A. & A.P. RR. estimated \$125,000 - Heavy rains on headwaters of Guadalupe during 26 th caused 4.5 ft rise -
17	85	72	13	8 ⁴⁵ AM	11 ⁴⁵ AM	.28	Cloudy	"	6 ⁴⁰	
18	86	75	11			.00	Clear	"	6 ⁵⁰	
19	85	75	10			.00	"	"	6 ⁵⁰	
20	89	76	13			.00	"	"	6 ⁵⁰	
21	89	76	13			.00	"	"	6 ⁵⁰	
22	88	76	12			.00	"	"	6 ⁵¹	
23	90	78	12			.00	"	"	6 ⁵⁰	
24	88	78	10			.00	"	"	6 ⁵⁰	
25	88	76	12			.00	"	"	6 ⁵⁰	
26	90	74	16	11 ⁴⁵ AM	6 ⁴⁵ AM	1.30	Partly Cloudy	"	7 ¹⁴	
27	97	74	23	6 ⁴⁵ AM	9 ²⁵ AM	.28	Partly Cloudy	"	6 ⁴⁵	
28	98	73	25			.00	Clear	"	7 ⁰³	
29	98	74	24			.00	"	6 ³⁵	6 ⁴⁸	
30	92	76	16			.00	Partly Cloudy	6 ¹⁰	6 ¹⁸	
31	84	72	12	12 ¹² PM	7 ¹⁸ PM	.37	PARTLY CLOUDY	6 ²⁰	6 ⁴⁰	
Sum	2767	2239	528			15.59				
Means	89.2	72.2	12.02			.503				

NOTE.—Observations are made as nearly as practicable at 8 a. m., 73th meridian time, or 9 a. m., 90th meridian time.

* For the 24-hour period ending at time of observation; as a rule the maximum being that for the previous day, and the minimum for the current day.

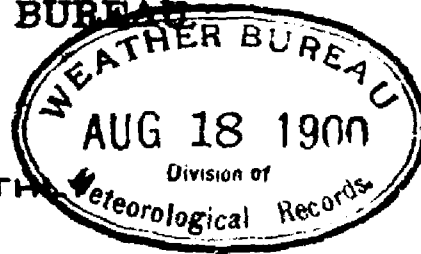
Allen
Cotton
[5,000, 1896.]

E. & J. L. Lelaine

J. H. Parsons
"Agent for Observer" Cotton-Region Observer.

U. S DEPARTMENT OF AGRICULTURE,

WEATHER BUREAU



MONTH

METEOROLOGICAL RECORD

OF

COTTON-REGION STATION

At Kerrville, Texas,

during JULY - 1900, 1899.

INSTRUCTIONS.

This form will be filled up in duplicate, one copy kept at the station, and the other forwarded to the observer in charge of the section center, not later than the 2d of the month succeeding that for which it is the record.

The daily observations must be entered in the proper columns *immediately after being taken*. Temperatures will be observed and recorded to the nearest whole degree.

A careful record of the times of beginning and ending of precipitation will also be noted upon the form. *When it begins to rain enter the time of beginning on the form, and when the rain ceases enter the time of ceasing.* Do not wait until observation time for making these entries. Instructions as to recording rainfall will be found on the new style measuring rods which have been furnished to all stations.

State of weather will be determined and recorded in accordance with the rules given in Instructions to Cotton Region Observers, 1897.

Each column of the form and every item in the summary must be correctly filled up.

Read carefully your copy of Instructions to Cotton Region Observers.

WILLIS L. MOORE,
Chief of Bureau.

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Tuesday, July 8, 2025 2:54 PM
To: Ross McKittrick
Cc: Travis Fisher; Judith Curry; Roy Spencer; John Christy; Josh Loucks
Subject: Re: New York Times inquiry

It's the uninformed speculation that will stick, not the delayed reality (recall the coral reef example we cite). So better sooner than later
Steven E. Koonin

On Jul 8, 2025, at 14:41, Ross McKittrick <ross.mckittrick@gmail.com> wrote:

I don't think anything is breaking, CNNis just regurgitating the NYT. MSNBC will be next but without any new details the story will fizzle. So I suggest not giving any info.

They clearly don't know what's happening although the guesses are reasonable. I prefer to let them speculate and collect crazy quotes from the usual corners and then release our work on our own timetable.

On Tue, Jul 8, 2025 at 2:31 PM Travis Fisher <travis.scott.fisher@gmail.com> wrote:
Fully agree!

I need to set up a notice and comment structure for the CWG report. We may also have to wait until the EPA releases its rule (as early as July 21), although I'd rather move first. That type of decision is well above my pay grade.

I'll keep you all posted.

On Tue, Jul 8, 2025 at 2:29 PM Steven Koonin <steven.koonin@gmail.com> wrote:
To be clear, I think the urgency is in CWG25.

The NCA5 critique could wait awhile.

Steven E. Koonin

On Jul 8, 2025, at 14:23, Travis Fisher <travis.scott.fisher@gmail.com> wrote:

I agree. I'm moving as fast as I can on that front.

The idea of the report is going to scare people much more than the report itself.

On Tue, Jul 8, 2025 at 2:21 PM Judith Curry <curry.judith@gmail.com> wrote:
since this is breaking, IMO it would be a good idea to release the reports
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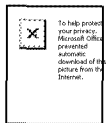
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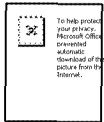
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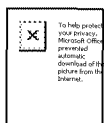
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Now it's CNN.
<Screenshot_20250708_115244_Outlook.jpg>

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Steven Koonin <steven.koonin@gmail.com>
Date: 7/8/25 9:58 AM (GMT-06:00)
To: 'Roy Spencer' <roywspencer@hotmail.com>, 'Ross McKittrick' <ross.mckittrick@gmail.com>, 'Judith Curry' <curry.judith@gmail.com>

Cc: 'Travis Fisher' <travis.scott.fisher@gmail.com>, 'John Christy' <climateman60@gmail.com>, 'Josh Loucks' <loucksj14@gmail.com>
Subject: RE: New York Times inquiry

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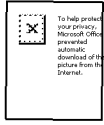
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<~WRD0003.jpg>



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CC: Steven Koonin [steven.koonin@gmail.com]; Roy Spencer [roywspencer@hotmail.com]; Judith Curry [curry.judith@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; Josh Loucks [loucksj14@gmail.com]
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Where did she get that goofy photo of me?

And the claim that I doubt human activity causes global warming is simply not true as evidenced by our publications.

I see Mann brought up heat waves and floods ... sometimes he just makes it too easy.

John C.

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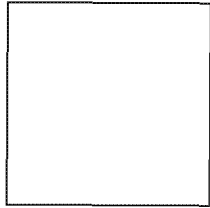
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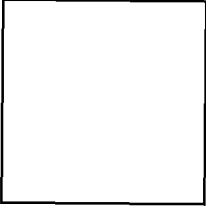
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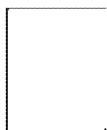
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To help protect
your privacy,
Outlook prevented
automatic
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I'm just following up on this inquiry. I'm planning to report that you're helping to lead a team of Energy Department employees who have been tasked with crafting a technical support document that justifies the repeal of the endangerment finding. Further, you are listed as a "special government employee" in the DOE internal email system.

Do you have any comment on this information? Please let me know at your earliest convenience -- I can be reached via email or via cell at 202-948-1924 -- and thanks again for considering this request.

Thanks,
Maxine

On Tue, Jul 1, 2025 at 5:11 PM Maxine Joselow <maxine.joselow@nytimes.com> wrote:
Hi Steve,

I hope this email finds you well. This is Maxine Joselow, a climate reporter for the New York Times. We previously spoke when I was at the Washington Post. I'm working on a story about the Environmental Protection Agency's forthcoming proposal to repeal the endangerment finding for greenhouse gases. Would you have time to speak with me about this sometime on Wednesday (tomorrow)? And if so, could you remind me of your phone number? Please let me know when you get the chance, and thank you for considering this request.

Best,
Maxine

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Maxine Joselow
Climate Reporter
The New York Times
Cell: 202-948-1924
Signal: MaxineJ.55

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Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Monday, July 7, 2025 10:32 PM
To: Travis Fisher
Cc: Roy Spencer; John Christy; Judith Curry; Ross McKittrick; Josh Loucks
Subject: Fwd: New York Times inquiry

Maxine making one last try. I will not respond.

Steven Koonin

Begin forwarded message:

From: Maxine Joselow <maxine.joselow@nytimes.com>
Date: July 7, 2025 at 22:19:55 EDT
To: steven.koonin@gmail.com
Subject: Re: New York Times inquiry

Hi Steve,

Just trying you one last time before the story runs. I'm planning to report that you are listed as a special government employee in the DOE internal email system, along with John Christy and Roy Spencer. If there's any comment you'd like to provide, please let me know. Thank you.

Best,
Maxine

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